26443

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Institut de génie des matériaux
Montréal (Québec)

National Research Council Canada
Industrial Materials Research Institute
Montréal, Quebec

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Institute

and

Society of Plastics Engineers
Quebec Section

1984 - Professional Development Program
in
Polymer Processing (PDP-84)

May 30 to June 1, 1984

J.-M. Charrier, B. Fisa, A. Catani, G. Salloum, P. VanGheluwe, G. Bélanger

1984 PROFESSIONAL DEVELOPMENT PROGRAMME
IN POLYMER PROCESSING
pdp "84"
MAY 30 - JUNE 1, 1984

No. 1 PLASTICS: APLICATIONS/PROPERTIES RELATIONSHIPS

J.-M. CHARRIER
IGM/McGill U.

JMC, 84/05/08

POLYMER ENGINEERING/TECHNOLOGY

THERMOPLASTICS
(high volume and related specialty plastics)

Polyethylene PE (LD, HD)
Ethylene-vinyl acetate EVA
Ethylene-ethyl acrylate EEA
Chlorinated polyethylene
Polypropylene
Polyallomer (block propylene/ethylene)
Polybutylene (butene 1)

Polyvinyl chloride PVC
Chlorinated polyvinyl chloride CPVC
Polyvinylidene chloride PVdC
Polyvinyl acetate PVAc
Polyvinyl alcohol PVAl
Polyvinyl formal
Polyvinyl butyral

Polystyrene PS
Polyacrylonitrile AN
Styrene-acrylonitrile SAN
Acrylonitrile-butadiene-styrene ABS
    blend-alloy, graft

Polymethyl methacrylate PMMA

Cellulose
Cellulose nitrate
Cellulose acetate CA
Cellulose acetate-butyrate
Ehyl cellulose

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POLYMER ENGINEERING/TECHNOLOGY

THERMOPLASTICS
(engineering and specialty plastics)

- Acetal, polyoxymethylene PDM
    - homopolymer
    - copolymer
- Polyamides
    - aliphatic
        - nylon 6
        - nylon 11
        - nylon 12
        - nylon 6-6
        - nylon 6-9
        - nylon 6-10
        - nylon 6-12
    - aromatic
        - aramids
    - amorphous
- Azole-based
    - poly benzimidazole
    - poly benzothiazole
- Polycarbonate PC
- Thermoplastic polyesters
    - polyethylene terephthalate PET
    - polybutylene terephthalate PBT/PTMT
    - copolyesters PCTA acid-modified
        PCTG glycol-modified
    - wholly aromatic polyesters
        - homopolyester
        - copolyester (polyarylate)
- Polyarylether
- Chlorinated polyether
- Fluoropolymers
    - homopolymers
        - PTFE polytetrafluoroethylene
        - PCTFE polychlorotrifluorsethylene
        - PVdF polyvinylidene fluoride
        - HFP polyhexafluoropropylene
        - PVF polyvinyl fluoride
        - PFA perfluoroalkoxy
    - copolymers
        - E - TFE
        - E - CTFE
        - FEP fluorinated ethylene propylene
- Imide-based
    - polyimide PI
    - polyamide-imide PAI
    - polyether-imide

- Ionomer
- Polyetheretherketone PEEK
- Ladder polymers
- Polyphenylene oxide PPO
- Parylene
- Polymethylpentene
- Silicone
- Polyphenylene sulfide PPS
- Sulfone-based
  polysulfone PSU
  polyethersulfone PESU
  polyarylsulfone
  polyphenylsulfone
- UHMW polyethylene

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POLYMER ENGINEERING/TECHNOLOGY

THERMOSETTING RESINS

Alkyds
Diallyl phtalates and isophtalates (Allyls) DAP, DAIP
Epoxies
Melamine and urea (amino) resins
Phenolics
1,2 polybutadiene
Unsaturated polyesters-styrene
Vinyl esters-styrene
Silicones

Diallyl maleates (DAM)
Triallyl cyanurate (TAC)
Poly diethylene glycol bis (allyl carbonate)
Furans

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POLYMER ENGINEERING/TECHNOLOGY

ELASTOMERS (RUBBERS)

Natural rubber, polyisoprene
Chloroprene (neoprene) (CR)
Polyisobutylene (butyl)
Polybutadiene (BR)

Ethylene-propylene rubber (EPR, EPT, EPDM)
Styrene-butadiene rubber (SBR)
Acrylonitrile-butadiene (nitrile) rubber (NBR)
Acrylate-butadiene (acrylic) rubber (ABR)

Chloro-sulfonated polyethylene (hypalon)
Organo-polysulfide (thiokol)
Silicone rubber
Urethane rubber
Fluoroelastomers (viton)
Carboxylic-modified NBR
Epichlorohydrin-based rubber

PVC/NBR blend

Thermoplastic elastomers

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STANDARD TESTING

MECHANICAL PROPERTIES

- short term (moderate speed loading)
   - tensile D638
      - modulus
      - yield stress
      - strength
      - elongation at break
   - flexural D790
      - modulus
      - strength
   - compression D695
      - modulus
      - yield stress
      - strength
   - shear D732
      - strength
   - hardness
   - Poisson's ratio
- very short term (high speed loading) impact
   - high speed stress - strain test D2289
   - drop weight test D3029
   - falling dart test D1709
   - falling ball impact
   - Izod impact test D256
   - Charpy test
   - tensile impact test D1822
- long term (moderate loading), creep
   - compressive load
      - deformation under load D621
   - tensile load
   - flexural load
   - creep curves
      - strain-time
      - apparent creep modulus
      - isochronous stress-strain
      - isometric stress-time

- long term creep failure
   - stress-time to failure curves

- long term, fatigue failure
   - loading mode
   - failure mode
   - S-N curves

- friction, wear, abrasion
   - coefficient of friction
   - limiting PxV
   - wear factor
   - abrasion test D1044

- high temperature effect
  - heat deflection temperature D648
  - Vicat softening point
  - deflection softening point
  - glass transition
  - crystalline melting point

- low temperature effect
  - brittleness temperature D746
  - cold bend temperature
  - cold flex temperature

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Chemical/environmental effects D543

factors
effects
tests

temperature, time
thermal aging D1299
temperature index UL746

chemicals
classification
water
"active" chemicals
"solvents"
miscellaneous
microorganisms
high energy radiations
weathering
outdoor exposure D1435
accelerated weathering D1499, D1501, D2565
flammability, combustion
flammability rating D635, UL94
oxygen index D2863
smoke emission density D2843
ignition D1929 UL746
flame spread rating E84

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Electrical properties

- volume resistivity D257
- surface resistivity
- dielectric constant D150
- dissipation factor, power factor D150
- dielectric strength D149
- tracking resistance D495

Thermal properties

- coefficient of linear thermal expansion D696
- specific heat
- thermal conductivity C177, C518

Optical properties

- transmission D10003, D1746
- absorption
- refractive index D542
- haze D10003
- gloss
- yellowness index D1925

Mass transport properties

- permeability
- solubility
- diffusivity

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HIGH-DENSITY POLYETHYLENE (HDPE)

Major markets

Market	1000 metric tons 1981
Blow molding	
Bottles	
Milk	239
Other food	70
Household chemicals	272
Pharmaceuticals/ cosmetics	66
Drums (15 gal. & larger)	27
Fuel tanks (all types)	9
Tight-head pails	26
Toys	12
Housewares	5
Other blow molding	45
Total blow molding	**771**
Extrusion	
Coating	15
Film (12 mil & under)	
Merchandise bags[a]	41
Tee-shirt sacks	1
Trash bags	4
Food packaging[b]	22
Deli paper	5
Other	55
Pipe	
Corrugated	151
Water	21
Oil & gas production	25
Industrial/mining	19
Gas	36
Irrigation	5
Other	9
Sheet (over 12 mil)	24
Wire & cable	50
Other extrusion	8
Total extrusion	**491**
Injection molding	
Industrial containers	
Dairy crates	18
Other crates, cases, pallets	35
Pails	87
Consumer packaging	
Milk-bottle caps	5
Other caps	20
Dairy tubs	34
Ice-cream containers	20
Beverage-bottle bases	45
Other food containers	5
Paint cans	10
Housewares	68
Toys	29
Other injection	77
Total injection molding	**453**
Rotomolding	30
Export	210
Other[c]	174
Grand total	**2129**

LOW-DENSITY POLYETHYLENE (LDPE)[a]

Pattern of consumption

Market	1000 metric tons 1981
Blow molding	27
Extrusion	
Coating	256
Film (12 mil & under)	1853
Pipe & conduit[b]	41
Sheet (over 12 mil)	6
Wire & cable	158
Other extrusion	27
Injection molding	238
Rotomolding	25
Export	447
Other[c]	338
Total	**3416**

EVA[a]

Pattern of consumption

Market	1000 metric tons 1981[b]
Extrusion	
Coating	25
Film	214
Wire & Cable	16
Other	3
Injection molding	17
Adhesives	40
Other	20
Export	40
Total	**375**

LLDPE[a]

Pattern of consumption

Market	1000 metric tons 1981
Blow molding	1
Extrusion	
Film (12 mil & under)	265
Pipe & conduit	30
Sheet & profile	2
Wire & cable	42
Injection molding	40
Rotomolding	20
Export	23
Other[b]	27
Total	**450**

LDPE[a]

Film markets

Market	1000 metric tons 1981
Packaging, food	
Baked goods	118
Candy	15
Dairy	22
Frozen food	37
Meat/poultry/ seafood	59
Produce	58
Packaging, retail carryout bags	
Tee-shirt sacks[b]	18
Other merchandise bags[c]	30
Grocery wetpack	15
Self service bags[d]	21
Garment bags[e]	45
Packaging, other	
Heavy duty sacks[f]	47
Industrial liners[g]	70
Rack and counter bags	79
Multiwall sack liners	15
Shrink wrap, pallet	30
Shrink wrap, other[h]	82
Stretch wrap	35
Textile	82
Packaging, misc. food, nonfood	205
Total packaging	**1083**
Nonpackaging	
Agriculture	59
Diaper backing	60
Household[i]	49
Industrial sheeting[j]	91
Nonwoven disposables	11
Trash bags[k]	529
Miscellaneous	45
Total non-packaging	**844**
Grand total	**1927**
Less tonnage from resold resin	−74
Adjusted total[l]	**1853**

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POLYSTYRENE (PS)

Major markets

	1000 metric tons
Market	**1981**
Molding (solid PS only)	
Appliances/consumer electronics	
Air conditioners	9
Refrigerators & freezers	11
Small appliances	14
Casettes, etc.	45
Radio/TV/stereo cabinets	43
Other	18
Furniture & furnishings	
Furniture	26
Toilet seats	9
Other	8
Toys & recreational	
Toys	48
Novelties	16
Photographic	23
Other	16
Housewares	
Personal care	23
Other	64
Building & construction	30
Misc. consumer & industrial	
Footwear (heels)	9
Medical	23
Other	14
Packaging & disposables	
Rigid pkg. & closures	73
Produce baskets	7
Tumblers & cocktail glasses	40
Flatware, cutlery	42
Dishes, cups, bowls	22
Blow molded items	11
Other injection	101
Total molding	**745**
Extrusion (solid PS only)	
Appliances/consumer electronics	
Refrigerators & freezers	18
Other	7
Furniture & furnishings	7
Toys & recreational	10
Housewares	10
Building & construction	13
Misc. consumer & industrial	9
Packaging & disposables	
Oriented film & sheet	51
Dairy containers	42
Vending & portion cups	66
Lids	46
Plates & bowls	16
Other extrusion, solid PS	52
Extrusion (foam PS)	
Board	32
Sheet	
Stock food trays	57
Egg cartons	25
Single-service	
Plates	24
Hinged containers	19
Cups (non-thermoformed)	7
Other foamed sheet*	8
Total extrusion	**519**
Expandable bead	
Billets	
Building & construction	58
Other	13
Shapes	
Packaging	32
Other	15
Cups & containers	60
Loose fill	11
Total expandable bead	**189**
Export	**68**
Other*	**117**
Grand total	**1638**

POLYPROPYLENE (PP)

Major markets

	1000 metric tons
Market	**1981**
Blow molding	
Medical containers	10
Consumer packaging	20
Total blow	**30**
Extrusion	
Coating	5
Fibers & filaments	471
Film (up to 10 mil)	
Oriented	107
Unoriented	30
Pipe & conduit	11
Sheet (over 10 mil)	16
Straws	14
Wire & cable	5
Other extrusion	11
Total extrusion	**670**
Injection molding	
Appliances	43
Furniture	18
Housewares	82
Luggage & cases	5
Medical	50
Packaging	
Closures	72
Containers & lids	49
Toys & novelties	36
Transportation	
Battery cases	59
Other	53
Other injection molding	98
Total injection	**565**
Export	**311**
Other*	**190**
Grand total	**1766**

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POLYVINYL CHLORIDE (PVC)

Major markets

	1000 metric tons
Market	**1981**
Calendering	
Building & construction	
Flooring	67
Paneling	11
Pool pond liners	16
Roof membranes	9
Other building	2
Transportation	
Auto upholstery/trim	32
Other upholstery/trim	8
Auto tops	5
Packaging: sheet	36
Electrical: tapes	4
Consumer & institutional	
Sporting/recreation	10
Toys	15
Baby pants	2
Footwear	14
Handbags/cases	11
Luggage	9
Bookbinding	2
Tablecloths, mats	17
Hospital & healthcare	7
Credit cards	8
Decorative film (adh.-back)	5
Stationery, novelties	2
Tapes, labels, etc.	6
Furniture/furnishings	
Upholstery	34
Shower curtains	5
Window shades/blinds/awnings	5
Waterbed sheet	4
Wallcovering	14
Other calendering	8
Total calendering	**368**
Extrusion	
Building & construction	
Pipe & conduit	
Pressure	
Water	362
Gas	1
Irrigation	111
Other	15
Drain/waste/vent	104
Conduit	168
Sewer/drain	155
Other	6
Siding & accessories	82
Window profiles	
All-vinyl windows	7
Composite windows	25
Mobile home skirt	7
Gutters/downspouts	2
Foam moldings	14
Weatherstripping	11
Lighting	8
Transportation	
Vehicle floor mats	8
Bumper strips	4
Packaging	
Film	115
Sheet	15
Electrical: wire & cable	167
Consumer & institutional	
Garden hose	18
Medical tubing	16
Blood/solution bags	20
Stationery/novelties	4
Appliances	13
Other extrusion	22
Total extrusion	**1480**
Injection molding	
Building & construction	
Pipe fittings	46
Other building	3
Transportation: bumper parts	5
Electrical/electronics	
Plugs, connectors, etc.	30
Appliances, bus. machines	17
Consumer & institutional	
Footwear	20
Hospital & healthcare	7
Other injection	15
Total injection molding	**143**
Blow molding: bottles	42
Compression molding: sound records	47
Dispersion molding	
Transportation	16
Packaging: closures	14
Consumer & institutional	
Toys	3
Sporting/recreation	8
Footwear	6
Handles, grips	6
Appliances	6
Industrial: traffic cones	6
Adhesives, etc.	
Adhesives	5
Sealants	4
Miscellaneous	5
Other dispersion	5
Total dispersion molding	**84**
Dispersion coating	
Building: flooring	56
Transportation	
Auto upholstery/trim	12
Other upholstery/trim	2
Anticorrosion coatings	5
Consumer & institutional	
Apparel/outerwear	6
Luggage	4
Tablecloths, mats	4
Hospital/healthcare	3
Furniture/furnishings	
Upholstery	8
Window shades/blinds/awnings	6
Wallcoverings	6
Carpet backing	7
Other	15
Total dispersion coating	**134**
Solution coating	
Packaging: cans	4
Adhesives/coatings	21
Total sol. coat.	**25**
Vinyl latexes: adhesives/sealants	25
Export	198
Grand total	**2546**

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PRINCIPAL
COMMERCIAL RESINS

B. FISA

DEFINITIONS

POLYMER - A pure chemical substance produced by a polymerization reaction

EXAMPLES

Natural polymers: cellulose
natural rubber

Synthetic polymers: polyethylene
cis - poly isoprene

RESIN - Commercial polymer based composition - may be a pure polymer but usually contains additifs - stabilizers fillers / plasticizers etc

EXAMPLES

flexible PVC
impact polystyrene
ABS
polyethylene pipe compound

U.S. PLASTICS SALES, 1982–1983

Material	1000 metric tons 1982	 1983
ABS	328	460
Acrylic	225	242
Alkyd	220	250
Cellulosics	46	52
Epoxy	137	147
Nylon ④	112	135
Phenolic	936	1115
Polyacetal ④	37	44
Polycarbonate ④	92	110
Polyester, thermoplastic (PBT, PET) ④	315	384
Polyester, unsaturated	386	450
Polyethylene, high density ①	2284	2646
Polyethylene, low density[a] ①	3494	3576
Polyphenylene oxide, modified ④	57	65
Polypropylene and copolymers ①	1647	1962
Polystyrene ③	1455	1608
Other styrenics	289	330
Polyurethane foams	674	755
Polyvinyl chloride and copolymers ②	2480	2761
Other vinyls	330	370
Styrene acrylonitrile (SAN) ③	39	41
Thermoplastic elastomers	183	200
Urea and melamine	512	602
Others[b]	45	60
Total	**16,323**	**18,365**

[a] Includes LLDPE

[b] Fluoroplastics, polybutylene, polyphenylene sulfide, polysulfone, etc

① Polyolefins - semicrystalline resins

② PVC - rigid polymer can be made soft by plasticizers

③ Styrene based polymers - transparent

④ Engineering plastics

Canadian resin statistics

CANADIAN RESIN CAPACITY (1000 tons)

Resin	Producer	In place 1/1/84	Additions
LDPE	Union Carbide	230	
	CIL	75	
	Dow	70	
HDPE	Dow	40	
LLD/HDPE	Du Pont	235	
	Esso	135	
	Union Carbide	115	
	Novacor	—	270[a]
	Dow	—	180[b]
PP	HiMont	68	
	Shell	68	
PS[c]	Dow	98	
	Polysar	75	
EPS	Potton	16	5[d]
	BASF	15	
	Texstyrene	9	7[e]
ABS	Borg-Warner	33	7[f]
	Monsanto	30	
PVC	BF Goodrich	140	
	Esso	100	
	Novacor (DS/AG)	100	
Polyester[g]	(Various)	55[h]	
Other[i]	(Various)	300[h]	
Total		**2007**	**469**

a Grassroots plant due on stream July 1984 at Red Deer, Alta
b Grassroots plant due 1986 at Fort Saskatchewan, Alta
c Excluding EPS bead
d Expansion at Mansonville, Que., due on stream during 1984
e Polymerization capacity to be added during 1984 at plant near Montreal
f Expansion at Cobourg, Ont., due on stream 1st quarter 1984
g Unsaturated
h Estimate by MODERN PLASTICS
i Acrylic, epoxy, nylon, phenolic, urethane chemicals, urea, and melamine

SELECTED CANADIAN RESIN MARKETS

	1000 metric tons							
	Domestic demand		**Imports**		**Exports**		**Sales of domestic resin[a]**	
Resins	**1982**	**1983**	**1982**	**1983**	**1982**	**1983**	**1982**	**1983**
LDPE[b]	317	348	32	50	124	93	409	391
HDPE	163	192	30	35	74	55	207	212
PP	93	104	12	15	40	43	121	132
ABS	36	46	8	7	1	3	29	42
PS[c]	146	153	26	24	12	14	132	143
PVC	171	220	22	40	53	55	202	235

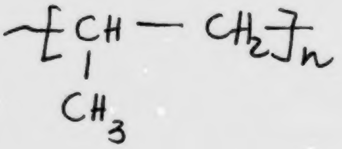
a Equals domestic demand minus import and plus export.
b Includes LDPE, LLDPE, and EVA
c Includes PS, EPS, and styrenic copolymers

POLYOLEFINS

ethylene $\quad\longrightarrow\quad$ polyethylene

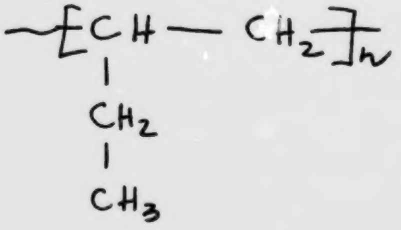
$$n\ CH_2{=}CH_2 \longrightarrow \sim\!\!\left[CH_2-CH_2 \right]_n\!\!\sim$$

Polyethylene $\quad -\!\left[CH_2-CH_2\right]_n \quad$ m.p. ~ 130°C

Polypropylene 

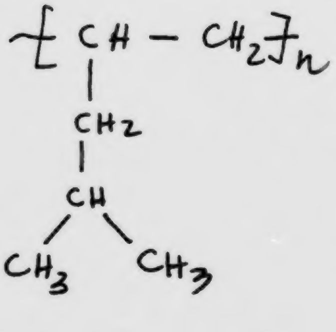
$$\sim\!\!\left[\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_2\right]_n$$

m.p. ~ 165°C

Polybutene 

$$\sim\!\!\left[\underset{\displaystyle \underset{\displaystyle CH_3}{\underset{|}{CH_2}}}{\underset{|}{CH}}-CH_2\right]_n$$

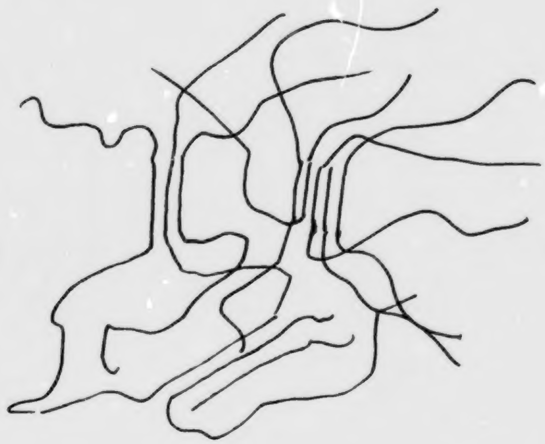
m.p. ~ 125°C

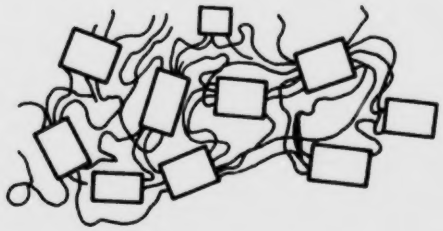
Polymethylpentene 

$$\left[\underset{\displaystyle \underset{\displaystyle CH(CH_3)_2}{\underset{|}{CH_2}}}{\underset{|}{CH}}-CH_2\right]_n$$

m.p ~ 240°C

PE, PP, PB are semicrystalline polymers





Crystalline PE density ~ .998 g/cm³
Amorphous PE density ~ .85 g/cm³ } 25°C

Crystallinity is related to density

$$C(\%) = 100 \cdot \frac{D_c(D - D_a)}{D(D_c - D_a)}$$

D - measured density, Da amorpous density, Dc crystalline density

POLYETHYLENE

Several types: HDPE, LDPE, LLDPE, HMW, UHMW

PROPERTIES DETERMINED BY:

Crystallinity
molecular weight (length)
molecular weight distribution

Crystallinity related to density

molecular weight related to melt index, higher the melt index lower the molecular weight

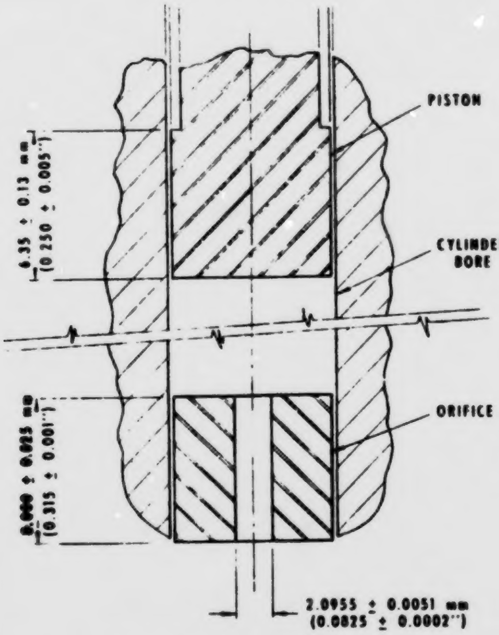

PISTON
CYLINDER BORE
ORIFICE
6.35 ± 0.13 mm (0.250 ± 0.005")
8.000 ± 0.025 mm (0.315 ± 0.001")
2.0955 ± 0.0051 mm (0.0825 ± 0.0002")

FIG. 2 Details of Extrusion Plastometer

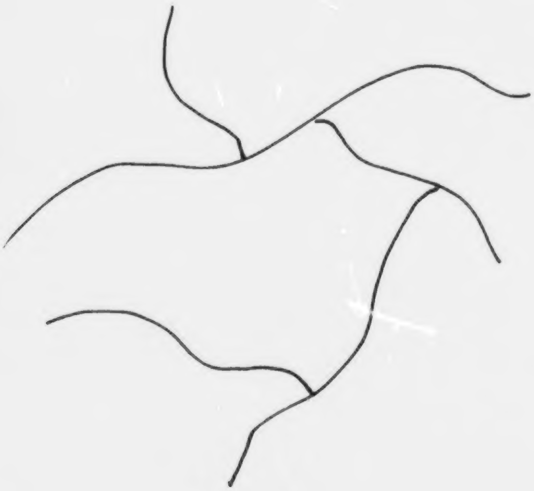
Effect of density and molecular weight on properties

Property	As density increases	As mol. weight increases
Abrasion resistance	↑	↑
Permeability	↑	
Impact strength	↓	↑
Tensile strength	↑	↑
Modulus (stiffness)	↑	
Hardness	↑	
Chemical resistance	↑	↑
Transparency	↓	
Melt viscosity		↑

LOW DENSITY POLYETHYLENE

LDPE

Polymerized at high pressure
Branched structure



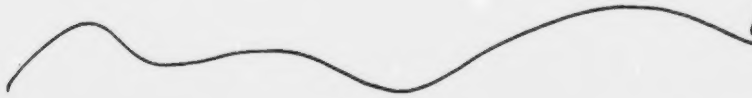
density 0.92–0.93g/cm³
crystallinity ~50%
melting point ~110°C

HIGH DENSITY POLYETHYLENE

HDPE

Polymerized at low pressure
Linear chains

density 0.95–0.97g/cm³
crystallinity ~80%
melting point ~133°C



Linear low density polyethylene - LLDPE

is really a copolymer

short branches

Ultrahigh molecular weight polyethylene - UHMWPE

LDPE

Advantages

Low cost
Chemical resistance
Flexibility
Toughness
Tasteless and odorless

Limitations

low tensile strength
resistance to bonding and printing
poor weathering resistance
high shrinkage

Applications

Bags
Packaging lids
wire and cable coatings
toys
pipes
Diaper backing

HDPE

Advantages and limitations

Same as LDPE but more rigid

Applications

Bottles
Waste baskets
Luggage
Pallets
Containers
Pipes (natural gas)
Dairy crates
Bags
Ice cream containers

UHMWPE

Advantages and limitations

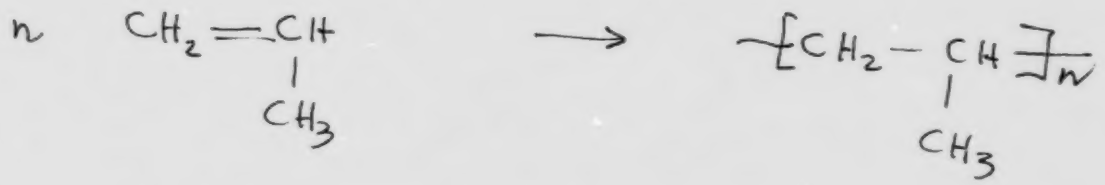
Abrasion resistance
Impact strength at high and low temperatures

Extremely difficult processing (does not flow)

Applications

gears , surgical implants

Polypropylene



$$n\ CH_2{=}CH(CH_3) \longrightarrow -[CH_2-CH(CH_3)]_n-$$

density $0.90-91\,g/cm^3$
m.p. ~165°C
glass transition temperature −10°C

Advantages

low cost
light weight
good impact strength
chemical resistance
Mold-in hinges possible

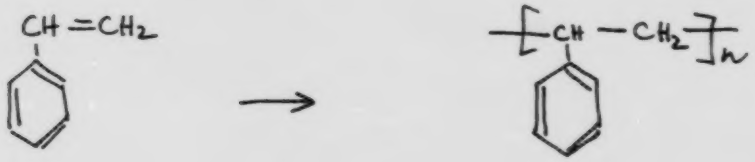
Limitations

poor weather resistance
brittle at low temp.
difficult to glue

Applications

battery cases
carpet backing
cords
caps and closures
pump housings
radio, TV housings
bottles
Straws

STYRENE POLYMERS



density	1.05 g/cm³
m.p	~100°C

Amorphous (non-crystalline)

Advantages	Limitations
Transparency	Brittle
Gloss	Low heat resistance
Hardness	Flammable
Rigidity	Poor weather resistance
Low Cost	

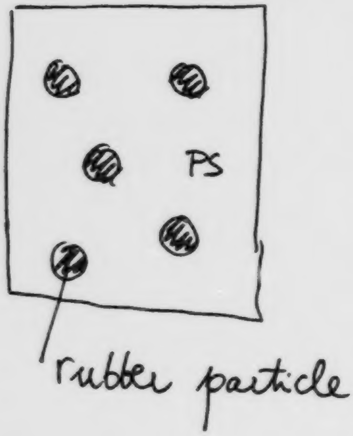
STYRENE - ACRYLONITRILE COPOLYMER
SAN

Compared to polystyrene SAN has somewhat
higher melting point
better mechanical properties

High impact polystyrene
HIPS

Modified by rubber - two phase system

opaque



Acrylonitrile - butadiene - styrene terpolymer
ABS

SAN modified by rubber

Styrene butadiene copolymer

~ S B SSSS B SSS B SSS B B SSSSS B ~

random

higher impact strength
reduced transparency

Thermoplastic rubbers

Block copolymers

SSSSSSSS BBBBBBBBB SSSSSSSS

EXPANDED POLYSTYRENE

Polystyrene particles impregnated with a volatile blowing agent (e.g. pentane)

APPLICATIONS

PS (solid)

Radio, TV, stereo cabinets
Air conditioners
Refrigerators
Furniture
Toys
Footwear (heels)
Cutlery
Dishes
Cups
Bowls
Cocktail glasses

PS (expanded)

Egg cartons
Plates
Hinged containers
Cups
Building materials (insulation)
Loose fill

SAN

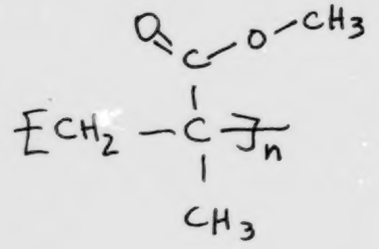
Appliances (blender and mixer bowls; fridge meat and vegetable compartments etc)

Instrument lenses
Typewriter keys
bottles and jars (Cosmetic)

ABS

Pipes
luggage
telephones
Calculator housing
auto dashboards

Polymethylmethacrylate



Sheet:
- cell casting
- continuous casting
- extrusion

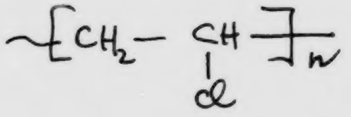
pellets:

Advantages	Limitations
Excellent optical properties	Brittle
Excellent wethearing	Poor scratch resistance
gloss	Combussible
	Solvent resistance

Applications

Interally lighted signs
Enclosures (swiming pools, shoping centers)
windshieds, mirrors, lenses etc.
signal lights, ~~m~~ nameplates etc.

Polyvinylchloride
PVC



$$\sim\!\left[\mathrm{CH_2}-\underset{\mathrm{Cl}}{\underset{|}{\mathrm{CH}}}-\right]_n$$

Amorphous and rigid (T_g ~75 - 100°C)

Amongst major polymers PVC is the least naturally stable - sophisticated stabilization systems are required

RIGID PVC

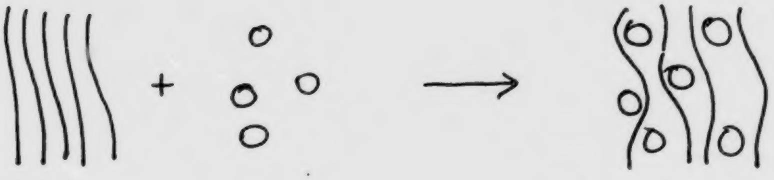
Resin
Stabilizers
Fillers
Pigments
⋮

Flexible PVC

Resin
⋮
plasticizers

Plasticizers

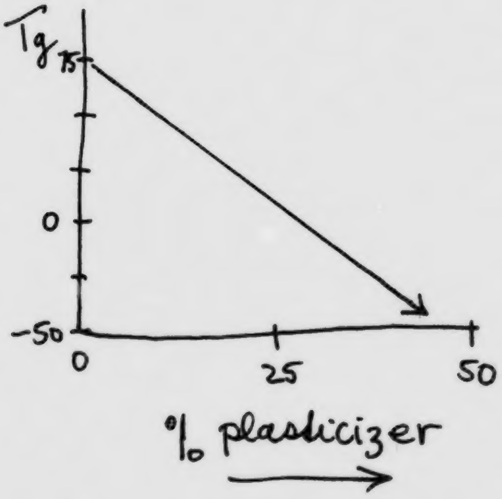
"Solvent like" materials incorporated into PVC to increase its flexibility



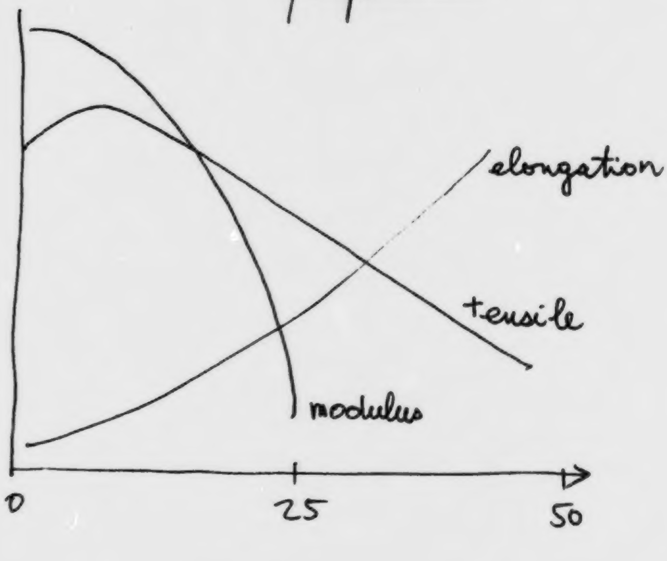
Plasticizers and polymer must be miscible i.e polymer must be soluble in the plasticizer and vice versa

80% of all plasticizers are used in PVC

25% of PVC plasticizers is DOP - dioctyl phtalate



Effect on physical properties



% plasticizer

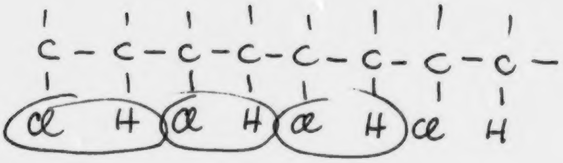
COMPOUNDING

Hot compounding

Dry blending

Plastisol

Degradation of PVC


C – C – C – C – C – C – C – C –
Cl H Cl H Cl H Cl H

heat
UV

Autocatalytic degradation

Stabilization

Neutralization of HCl
Displacement of labile Chlorine
Reaction with double bonds

PVC

Advantages

Non flammable
Good weathering resistance
Dimensional Stability
Extremely versatile
Low cost

Limitations

Higher density than other plastics
Limited thermal stability

PVC

Applications

Rigid PVC

- Pipe (water, gas, irrigation, drain)
- Conduit
- Siding
- Window profiles
- Gutters
- Credit cards
- bottles
- records
- traffic cones
- window shades

Flexible

- Flooring
- Pool liners
- Garden hose
- Shower curtains
- Upholstery
- packaging sheets
- tablecloth

Nylons

Nylon - generic name for polyamide

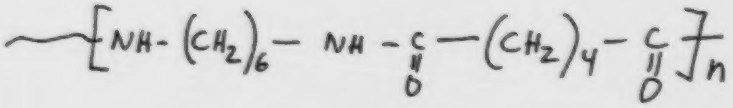
6, 66, 610, 11, 12

Nylon 66

hexamethylene diamine adipic acid

$$H_2N(CH_2)_6NH_2 \quad + \quad HOOC(CH_2)_4COOH$$

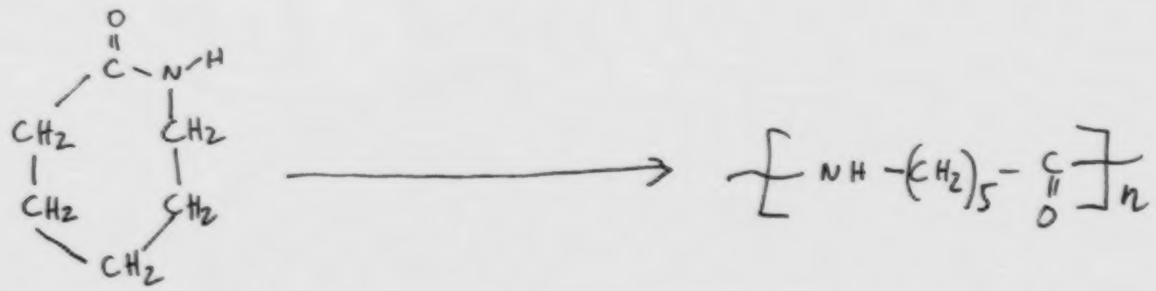
$$\downarrow$$



$$\sim\!\left[NH-(CH_2)_6-NH-\underset{\displaystyle O}{\overset{}{\underset{\|}{C}}}-(CH_2)_4-\underset{\displaystyle O}{\underset{\|}{C}}\right]_n$$

nylon 66

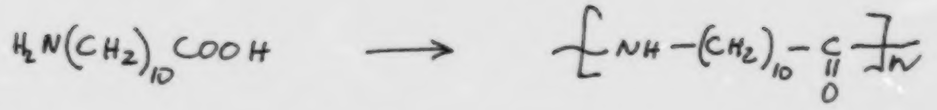
Nylon 6



$$\left[NH-(CH_2)_5-\underset{\displaystyle O}{\underset{\|}{C}}\right]_n$$

poly - ε- caprolactame nylon 6

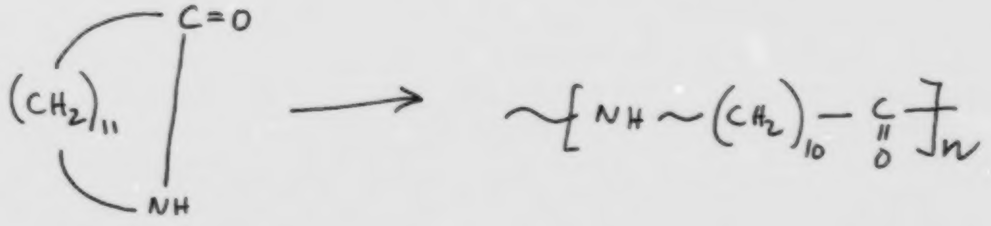
Nylon 11



$$H_2N(CH_2)_{10}COOH \longrightarrow \left[NH-(CH_2)_{10}-\underset{\underset{O}{\|}}{C} \right]_n$$

11 amino undecanoic acid — nylon 11

Nylon 12


C=O
$(CH_2)_{11}$
NH
$\sim\left[NH\sim(CH_2)_{10}-\underset{\underset{O}{\|}}{C} \right]_n$

lauryllactame — nylon 12

Nylons are semicrystalline polymers

	m.p
Nylon 6	210-225°C
Nylon 66	250-260°C
Nylon 11	180 - 190°C
Nylon 12	175-180°C
(Polyethylene)	135°C

Hydrogen bonds

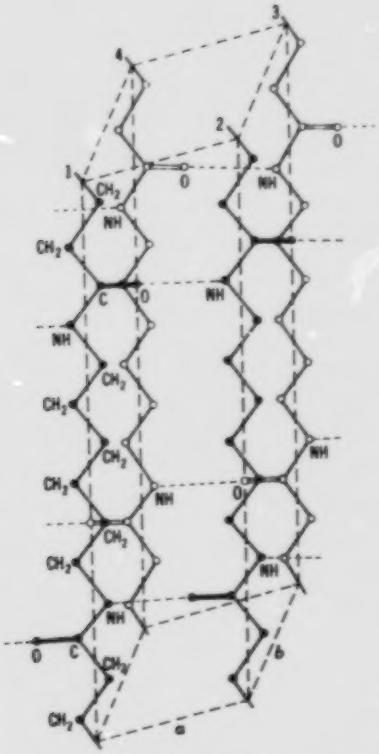


Fig. 21. Elementary cell of nylon-6,6 (alpha form according to Bunn). The dotted lines C=O···HN indicate the hydrogen bridge bonds.

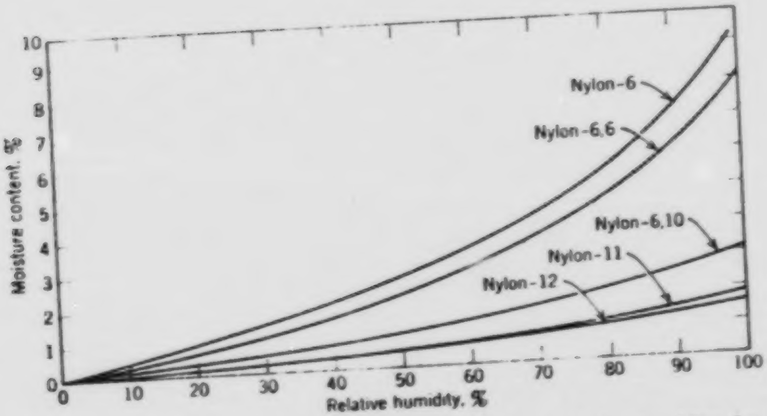


Fig. 1. Variation of equilibrium moisture content with ambient relative humidity for molded nylons.

Effect of crystallinity on properties

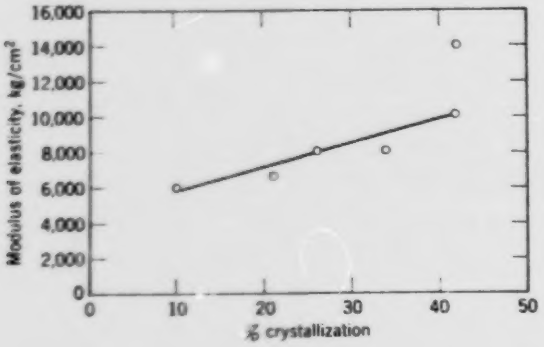


Fig. 18. Modulus of elasticity of dry nylon-6,6 as a function of degree of crystallinity.

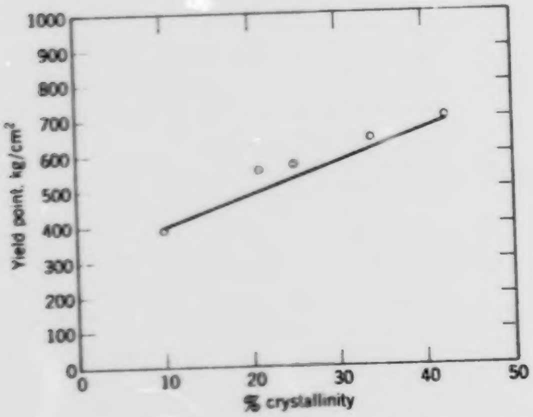


Fig. 19. Yield point of dry nylon-6,6 as a function of crystallinity.

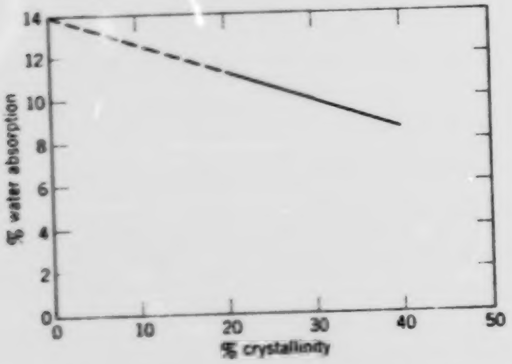


Fig. 20. Water absorption of nylon-6,6 as a function of crystallinity at 100% rh and room temperature.

Nylons are hygroscopic

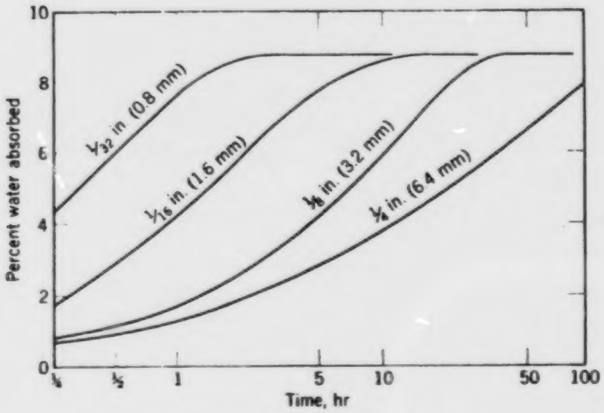


Fig. 2. Rate of water absorption of nylon-6,6 in boiling water.

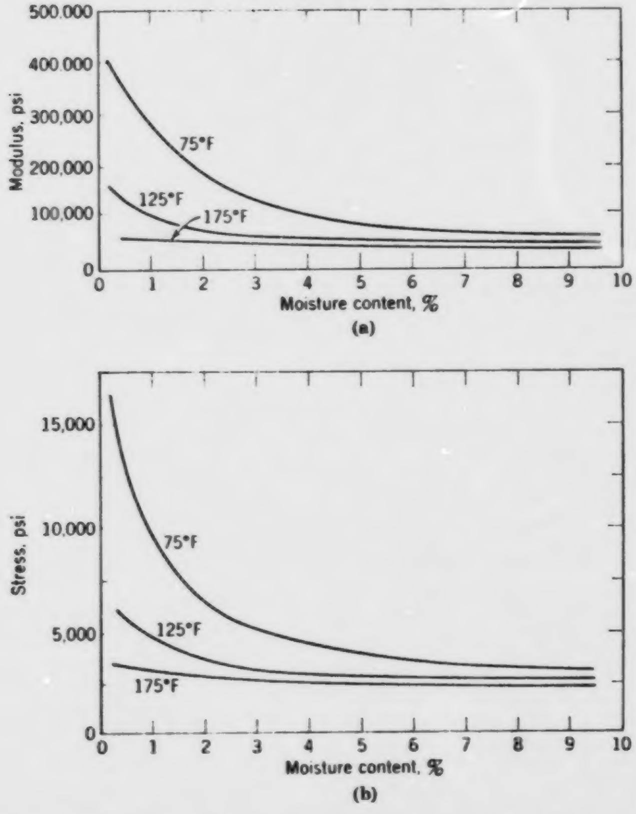


Fig. 4. Effect of moisture content and temperature on flexural properties of nylon-6: **(a)** modulus of elasticity; **(b)** yield stress.

REINFORCED NYLON

Fibers (Glass, Carbon)
Flakes (Mica, glass)

Table 6. Effects of Fiber Length on Properties of Reinforced Nylon

Physical property	ASTM test method	Unfilled nylon-6	30% Short glass fiber (<⅛ in.)	30% Long glass fiber (>¼ in.)
density, g/cc	D 792	1.13	1.34	1.34
water absorption, %, 24 hr	D 570-57T	1.6	1.1	1.1
tensile strength, psi	D 638-58T	11,800	22,000	22,000
ultimate elongation, %	D 638-58T	200	2	5
flexural modulus, psi	D 790-58T	380.000	1,000,000	950,000
Izod impact strength, ft-lb/in. notch	D 256-56	1.1	1.4	3.6

Table 7. Effect of Fiber Content on Properties of Reinforced Nylon

Physical property	ASTM test method	Unfilled nylon-6	30% Long glass fiber	40% Long glass fiber
density, g/cc	D 792	1.13	1.34	1.52
water absorption, %, 24 hr	D 570-57T	1.6	1.1	0.8
tensile strength, psi	D 638-58T	11,800	22,000	30,000
ultimate elongation, %	D 638-58T	200	5	5
flexural modulus, psi	D 790-58T	380,000	950,000	1,200,000
Izod impact strength, ft-lb/in. notch	D 256-56	1.1	3.6	5.0

NYLONS

Advantages

good mechanical properties
(tensile
fatigue
impact
friction
abrasion

Chemical resistance
Heat deflection temperature (esp. reinforced grades)

Limitations

high shrinkage
moisture sensitive
difficult processing (narrow melting range, drying)

Applications

Textiles
Gears
Bearings
Brushes
Appliance housing
Hinges
WIRES AND CABLES
Films
Fans

RIM

POLYACETAL

$\sim\!\left[CH_2-O\right]\!\sim$

polyformaldehyde
polyoxymethylene

m.p. 181°C
density $1.42\,g/cm^3$

highly crystalline

homo polymer
co polymer

Advantages

mechanical properties (tensile, stiffness, fatigue, friction creep)
oil resistant

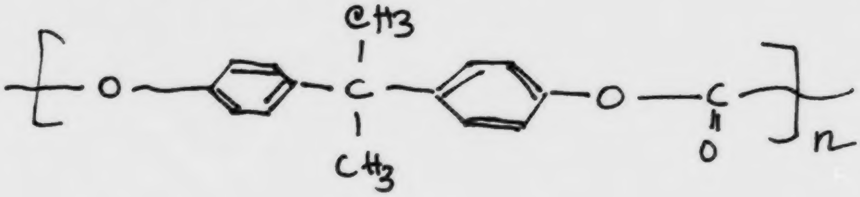
Limitations

Poor acid, base UV resistance
Difficult to bond
High shrinkage

Applications

gears,
meat hooks
ski bindings
zippers

Polycarbonate



Amorphous polymer – transparent

m.p. ~150°C
Density 1·2g/cm^3

High impact strength

Advantages
high impact strength between −100°C and 130°C

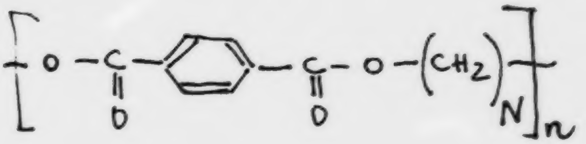
Limitations

Poor solvent and scratch resistance
cost

Applications
Bottles
Safety glass
Lenses
power tool housings
helmets
Lighting, signs etc

THERMOPLASTIC POLYESTERS

PET – polyethylene terephtalate
PBT – polybutylene terephtalate



PET N=2
PBT N=4

PET – crystalline or amorphous

density 1.30 – 1.39
m·p· 255°C

PBT crystalline

density 1·31 g/cm^3
m·p· 225°C

PET (amorphous)

Advantages	Limitations
Transparent Good barrier properties Lightweight	Difficult processing

Applications

Bottles - soft drinks
- spirits

Film - boil-in pouches

PET (crystalline), PBT

Advantages	Limitations
Mechanical Properties low moisture pick-up	High shrinkage Hydrolysis (>60°C)

Applications

pump housings, impellers
iron, toaster housing
cooker, fryer handles
hair dryer nozzles
gears, rotors

CELLULOSICS

$\left.\begin{array}{l}\text{Cellulose nitrate}\\ \text{Ethyl cellulose}\\ \text{Cellulose acetate}\end{array}\right\}$ chemically modified cellulose

⋮

Advantages	Limitations
Transparency	Poor solvent and alkali resistance
Pleasant hand	Moisture sensitive
Toughness	Flammable
Easy processing	

Applications

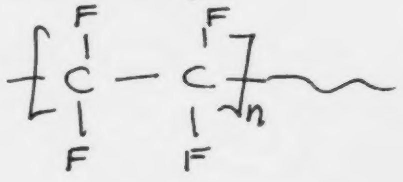
Tool handles
Blister packaging
pencil barrels
eyglass frames
steering wheels
brush handles
skylights
outdoor signs

FLUOROPLASTICS

Tetrafluoroethylene $CF_2 = CF_2$

Polytetrafluoroethylene

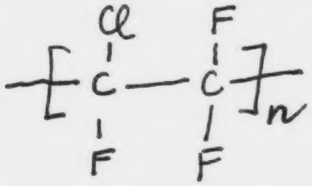
PTFE



$$-\!\left[\underset{F}{\overset{F}{C}}-\underset{F}{\overset{F}{C}}\right]_n\!\sim$$

m.p. 327°C
density $2.15 g/cm^3$

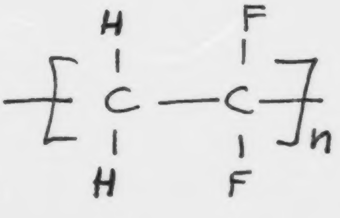
Polychlorotrifluoroethylene



$$-\!\left[\underset{F}{\overset{Cl}{C}}-\underset{F}{\overset{F}{C}}\right]_n$$

m.p 218°C
density 2.13

Polyvinylidene-fluoride



$$-\!\left[\underset{H}{\overset{H}{C}}-\underset{F}{\overset{F}{C}}\right]_n$$

m.p 170°C
density $1.78 g/cm^3$

---

and several others

Advantages

chemical resistance
low coefficient of friction
self lubricating
non flammable
useful between -200°C to 260°C
(PTFE)

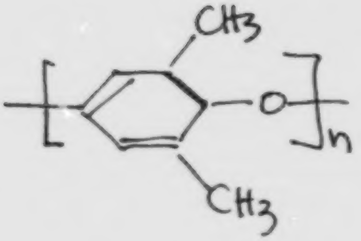
Limitations

very high cost
difficult processing
high creep

Applications

linings of chemical processing equipment
high temp. cable insulation
non stick applications
bushings
film, sheets, rods
coatings
valve components
etc.

Polyphenylene oxide
(PPO)



modified with polystyrene

m·p 280–310°C
density 1·05

Advantages

high heat deflection temp. (80 – 150°C)
low creep
ductile impact failure

Limitations

solvent sensitivity

Applications

Shower heads
auto dashboards, trim, grilles
Valve, pump components

SOME OTHER THERMOPLASTICS

SULFONE POLYMERS	High temperature resistance good electrical insulation (hairdryer comb)
Polyetherimide	high heat resistance stiffnes strength
Polyetherether ketone (PEEK)	wire / cable insulation (high performance)
POLY IMIDE	high heat resistance

etc
etc.

PRINCIPLES OF PLASTICATING EXTRUSION OF THERMOPLASTICS

A - INTRODUCTION

1 - Importance of the extrusion process
2 - Main extruder components

B - EXTRUSION PROCESS MAIN PARAMETERS

1 - Extrusion equipment
2 - Downstream equipment
3 - Thermoplastics properties
4 - Extruder operational principles

C - TROUBLE SHOOTING-EXTRUDER

A. Catani

A - INTRODUCTION

1- Importance of the extrusion process

In the plastic Industry the most widely used processing method with about 45% of the processed structural volume is extrusion. It dominates in the continuous manufacture of such shapes as rods, profiles, tubing, film/sheet, monofilaments, pipe and as outer layer on wire and cable. It also is used for such other intermediate uses as the formation of a molten tube (parison) in blow molding, and an integral component for completing the mixing or compounding of plastics materials and in the conversion of compounded material into pellet form.

Of the estimated total of 12,500 million lbs processed in U.S. by extrusion, the most common polymers used are LDPE with 4,950 million lb, PVC with 3,150 million lb, polystyrene (including sheet and SAN) with about 1,380 million lb, HDPE with 1,200 million lb, polypropylene with 500 million lb, ABS with about 400 million lb and thermoplastic polyester with 500 million lb. Smaller amounts of cellulosics, other vinyls, acrylics and such grades of engineering thermoplastics as acetals, polyfluocarbons, nylons and polycarbonates are also extruded. The consumption of extruded plastics by major markets as defined by the SPI is shown on Table 1. As a comparison, similar information is given on Table 2 for injection molded thermoplastics.

2- Main Extruder Components

An example of the most important components for an extruder are shown on Fig. 1 and 2. The heart of an extruder is the polymer screw. Fitted tightly within a precisely machined cylinder or barrel, the screw is rotated by a high torque speed reduction drive system to move material along its length. The screw itself is a special worm with flights that are usually of one pitch, i.e. the pitch is equal to the screw diameter. At the feed end, the root diameter is small so that a deep channel is formed between flights to convey material easily into the barrel. Farter

TABLE 1. U.S. MARKET CONSUMPTION OF EXTRUDED PLASTICS 1981

Market	Million lb	%	Major polymer
Packaging	5,200	41.6	LDPE
Building and construction	3,540	28.3	PVC
Consumer and institutional	1,375	11.0	LDPE
Electrical/electronic	1,275	10.2	PVC, LDPE
Transportation	90		ABS
Industrial machinery	15		--
Other	1,005		PVC
TOTAL	12,500		

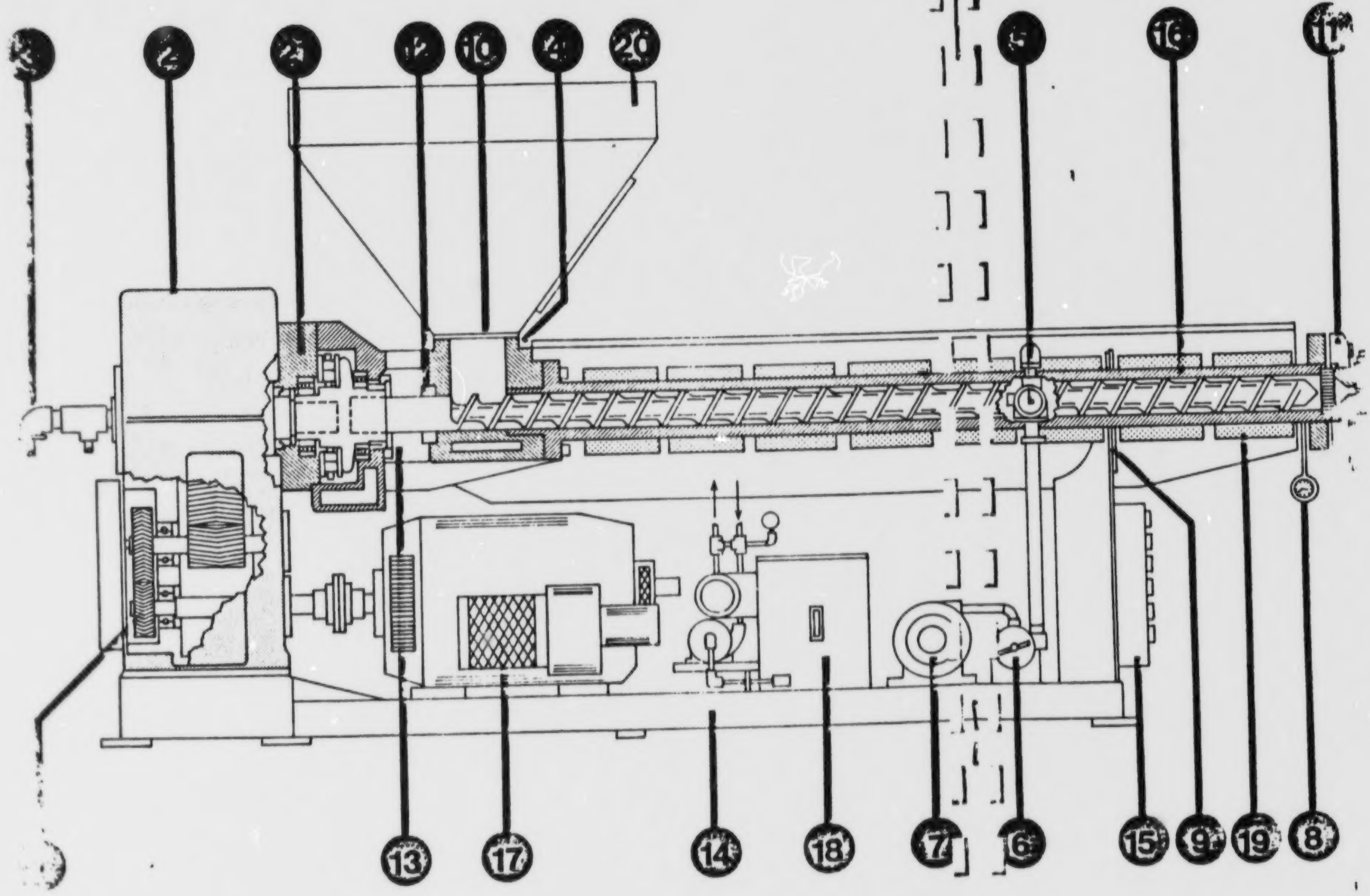
Note: SPI market definitions.
Source: Estimates by C.H. Kline & Co.

TABLE 2. CONSUMPTION OF INJECTION MOLDED PLASTICS BY MARKET 1981

Market	Million lb	Major polymer
Consumer & institutional	2,060	PS, LDPE
Packaging	1,085	HDPE
Transportation	870	PP
Electrical/electronic	805	PS
Building and construction	325	PVC, ABS
Industrial/machinery	240	PS
Furniture & furnishings	95	PS
Other	620	PS, HDPE
TOTAL	6,100	

Note: SPI market definitions.
Source: Estimates by C.H. Kline & Co.

FIG. 1


2
12
10
4
20
5
16
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17
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7
6
15
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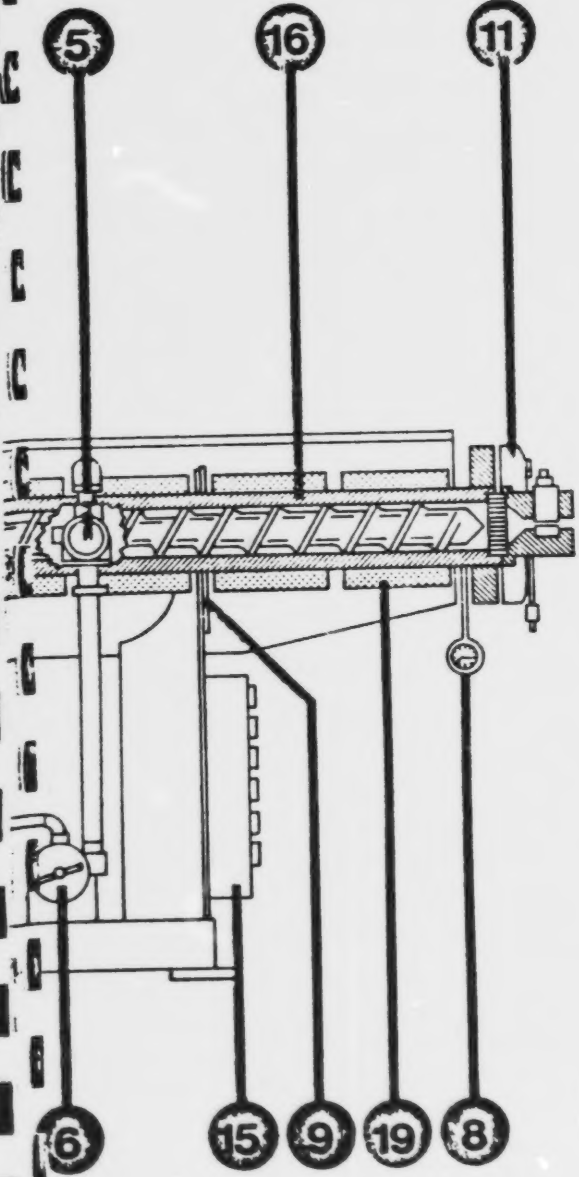
8

TORQUE MASTER

Vented, Water-Cooled Extruder



① **CHANGE GEARS**—For selection of most efficient extruder screw and drive motor operating speed for the thermoplastic material being extruded.

② **GEAR REDUCER**—All-herringbone gear reducer assures minimal frictional losses and the transmission of maximum available horsepower to the extruder screw. Change gears provided as standard.

③ **ROTARY UNION**—Permits temperature control of cored screw when required with either water or oil.

④ **FEED THROAT**—Cored for circulation of cooling or heating medium.

⑤ **SIDE VENT**—Provided with vacuum tight stack with hinged inspection port. Vent stack easily removable to convert machine to non-vented operation by using a vent plug and clamp ring.

⑥ **TRAP**—Vacuum pump trap provided with washable filter, condenses volatiles and traps any powders drawn from the extruder. The trap minimizes vacuum pump clogging.

⑦ **VACUUM PUMP**—High capacity water pump removes volatiles from the plastic during venting.

⑧ **PRESSURE MEASUREMENT**—A wide range of pressure indicators and recorders are available to measure extruder head back pressure.

⑨ **FRONT BARREL SUPPORT**—Permits axial and radial expansion of extruder barrel while maintaining precise barrel alignment. The support is rugged and located far downstream to support heavy dies.

⑩ **LARGE RECTANGULAR FEED OPENING**—For uniform and easy feeding of a wide range of thermo-plastic materials. Round hole feed opening is available as an option.

⑪ **HINGED SWING GATE**—Quick opening and designed to seal at high head pressures. The swing gate is heated and includes shear pins to protect against excessive head pressures. Front gates are interchangeable by simply removing hinge pin.

⑫ **REAR SEAL**—Easily accessible, prevents plastic leakage rearward. An optional heated rear seal is available to prevent powder leakage rearward. The heated seal fuses the migrating powder, thus sealing the gap between the screw and the bushing. The heater is controlled by a powerstat.

⑬ **LARGE AIR SPACER**—Located between feed throat and thrust bearing assembly serves as a good thermal insulation. Large space permits easy access to feed throat rear seal and thrust housing labyrinth.

⑭ **EXTRUDER BASE**—Fabricated from thick, bent steel plate, and internally reinforced. The integral base provides a vibration-free support for extruder components and a solid support for the generated extruder torques.

⑮ **ELECTRICAL BOX**—For power and thermocouple outlet for head, die and some auxiliary components.

⑯ **HEAVY WALL CYLINDER**—Internally and integrally lined with a hard boron-containing alloy for longer life. The cylinder is designed for continuous operation up to 10,000 psi.

⑰ **MOTOR**—Adjustable speed drives, solid state D.C. or eddy current clutch are available. In the TM model the motor mounts underneath the extruder thrust housing and barrel and is directly coupled to the reducer input shaft.

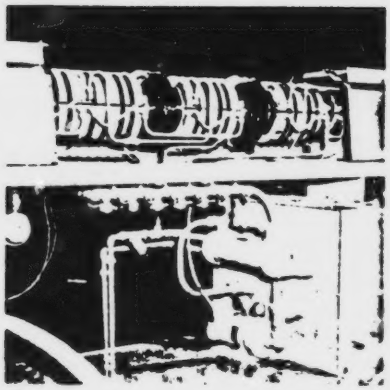
⑱ **BARREL WATER COOLING SYSTEM**—Closed, recirculating system includes reservoir, motor, pump, heat exchanger and required controls for precise barrel temperature control.

⑲ **BARREL HEATING AND COOLING**—Uses heavy wall, cast aluminum heaters having a cast-in resistance element for heating and a cast-in stainless steel coil for cooling.

⑳ **HOPPER**—Large capacity hopper provided with sight glass, shut-off slide and drain chute.

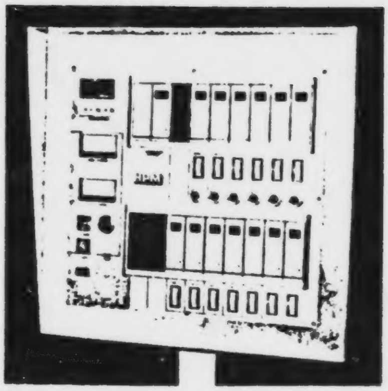
㉑ **THRUST BEARING ASSEMBLY**—High capacity thrust and radial bearings assure continuous and reliable

FIG. 2



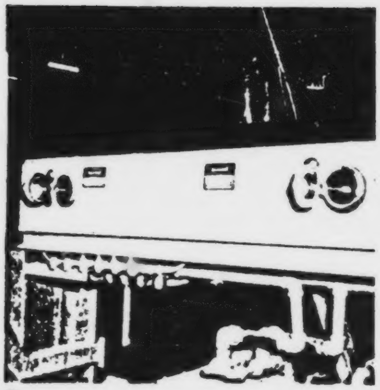
1 Cooling System

Efficient, high-capacity cooling is provided by a closed, recirculating system which includes reservoir, motor, pump, heat exchanger and required controls.



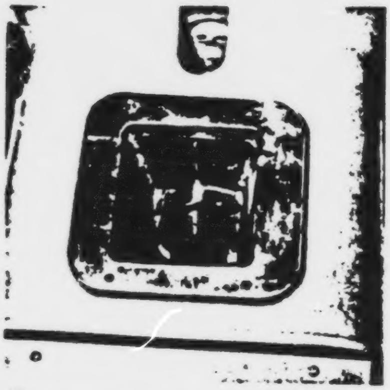
2 Operator Console

Solid-state control system assures precise temperature and speed regulation. The HPM DATA series instrumentation is simple to set and read, reliable and easy to maintain.



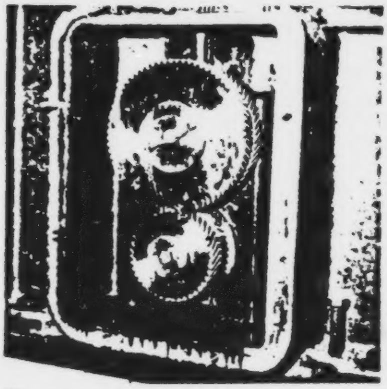
3 Dual Vent

Patented process for removal of volatiles and moisture from hygroscopic polymers with reduction or elimination of costly predrying. Eliminates product defects associated with moisture or volatiles contamination.



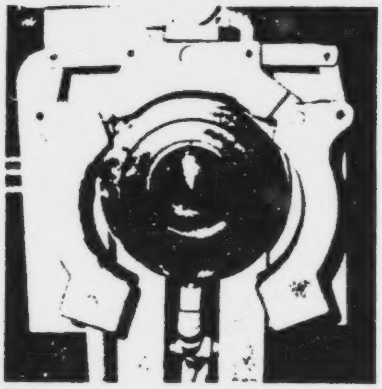
4 Feed Throat

Cored for circulation of cooling medium; large opening prevents bridging.



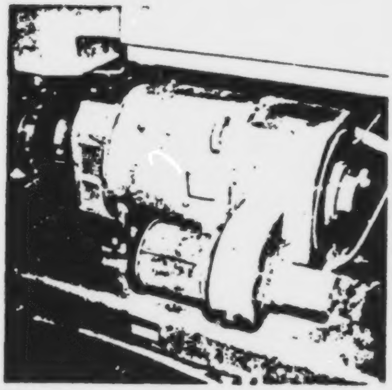
5 Change Gear

For selection of efficient extruder screw and drive motor operating speed. • Standard



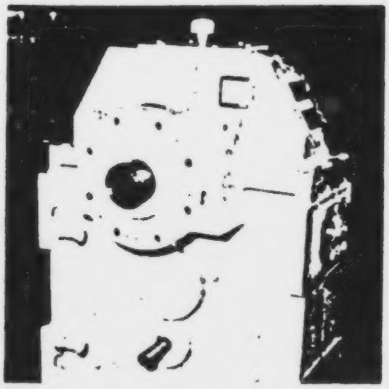
6 Quick Clamp

Fast screw changes mean more profits. Quick clamp retains the die and adapter without leakage. (Optional clamp)



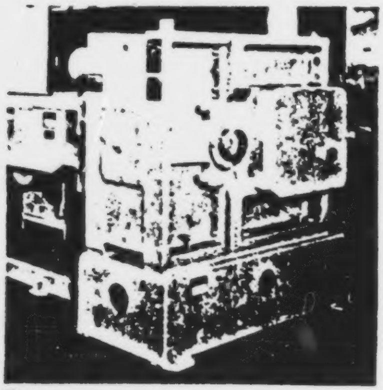
7 Drive

Available in many horsepower ratings and various speed ranges. Solid state, DC are standard. Drives are factory-mounted below barrel or alongside barrel for horizontal reducers to insure accurate alignment and reduce base vibration.



8 Integral Thrust Bearing Box

High-capacity thrust and radial bearings assure continuous and reliable operation.



9 Horizontal Gear Box

Both helical and herringbone gear reducers minimize friction losses and assure transmission of maximum available horsepower to extruder screw. Available in horizontal or vertical designs for variable center-line heights.

along, the root diameter increases to form a smaller channel and apply greater pressure on the plastic material.

Electric resistance heaters clamped tightly to the outside of the barrel conduct heat to the plastic material within. More importantly, the rotation of the screw shears the plastic material creating even greater heat. In combination with the increased pressure applied by the screw, this heat melts the material so that it can be mixed and formed into a uniform melt ready for the next stage of the forming process as it exists the extruder. Given the variety of forces, speeds, temperatures and pressures at which the extruder must operate, its design demands a highly refined technology.

B- THE EXTRUSION PROCESS MAIN PARAMETERS

A general block diagram of the basic inputs and outputs of the extrusion process is shown in Fig. 3.

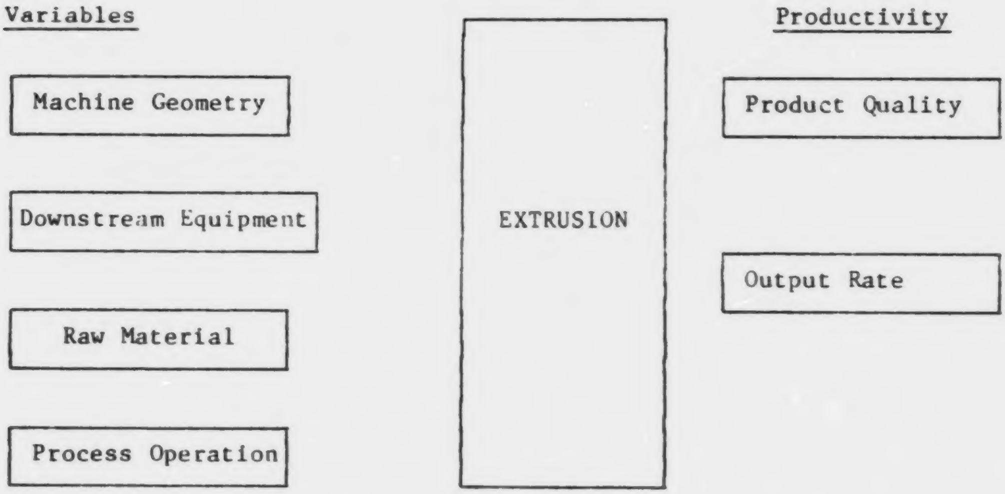

Variables
Machine Geometry
Downstream Equipment
Raw Material
Process Operation
EXTRUSION
Productivity
Product Quality
Output Rate

Fig. 3 Extrusion process.

Group 1 and 2 variables include design of hopper, screw, heaters, die, take-off, puller, saw, etc; all are under the control of the machine builder and quite often as requested by the buyer.

Group 3 variables include variations in such properties as specific heat, thermal conductivity, friction characteristics, bulk density, etc.

Group 4 of fig. 3 can be subdivided into machine variables such as barrel and die temperature profiles, screw speed, and process variables (mainly melt temperature, amperage, and pressure).

Obviously every possible attempt should be made to control these variables but some variation will still occur. The effect on final product quality will depend on several factors, not the least of which is high throughput. This is particularly severe in the area of homogeneity. The conflicting requirements of greater quality and higher throughputs make it essential to control all machine variables very tightly and make control of process variables more desirable. It must be pointed out, however, that the latter requires complex transducers and a good knowledge of machine-control interrelationships and hence should only be contemplated once the tightest control possible on all machine variables still does not give the desired result.

C- VARIABLES AFFECTING PRODUCTIVITY AND QUALITY

1. EXTRUSION EQUIPMENT

a) The right size extruder

Traditionally, extruder sizes have been given as the nominal inside diameter of the cylinder. While this is a good index of the physical dimensions of the machine, it is a poor index of productivity.

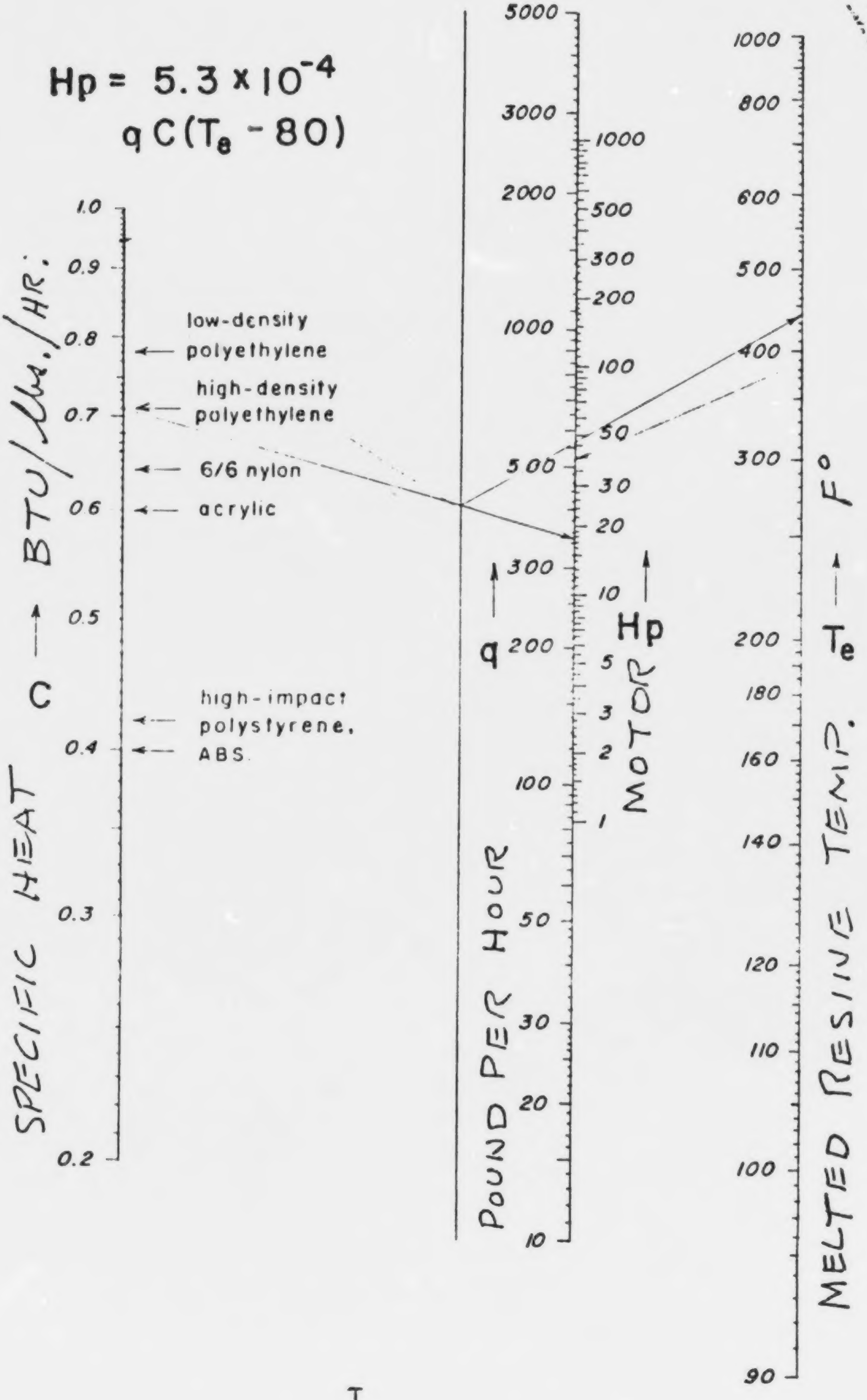
Considering the extruder as a whole, the pumping section consumes only a small part of the energy needed. The main requirement of the extruder is to convert the cold pellets to a hot, uniform melt. The power consumed as hydraulic energy in pumping 100 lb/hr of polyethylene against a head pressure of 5000 psi is less than 1 hp, for example, while the power to raise its temperature from 80°F to 350°F is nearly 11 hp. Pratically all this power must come from the shearing action of the screw. Because the various plastics are heated to different processing temperatures and require different amounts of heat per pound processed, the extruder output, per horsepower of input, varies according to what resin is being processed.

Available horsepower, therefore, is a much more realistic gage of the productive capacity of the extruder than is screw diameter.

The relationship between drive horsepower, melt temperature in the die, and output is given in the nomogram I, for a number of representative thermoplastics. This chart is based on the following assumptions: 1) The material enters the extruder at 80°F; 2) The hydraulic energy consumes about 5% of the total; 3) The average specific heat from 80° to the middle of the processing range applies approximately to the entire processing range; 4) the over-all efficiency of motor and beltless transmission is 80%. These are not precise values but should be close enough for estimating purposes.

The capacity figure used in sizing the extruder should also be realistic in the sense that it should not greatly exceed the projected capacity of the cooling and take-off system for the extrudate. In the present state of extrusion technology, the speed of take-off is more likely than the extruder to be the capacity-determining element of the system.

Once the material, die-melt temperature, and gross output are known, the power nomogram can be used to find the horsepower. It has been our experience that with most plastics, peripheral screw speeds should not



$$Hp = 5.3 \times 10^{-4} \, qC(T_e - 80)$$

I

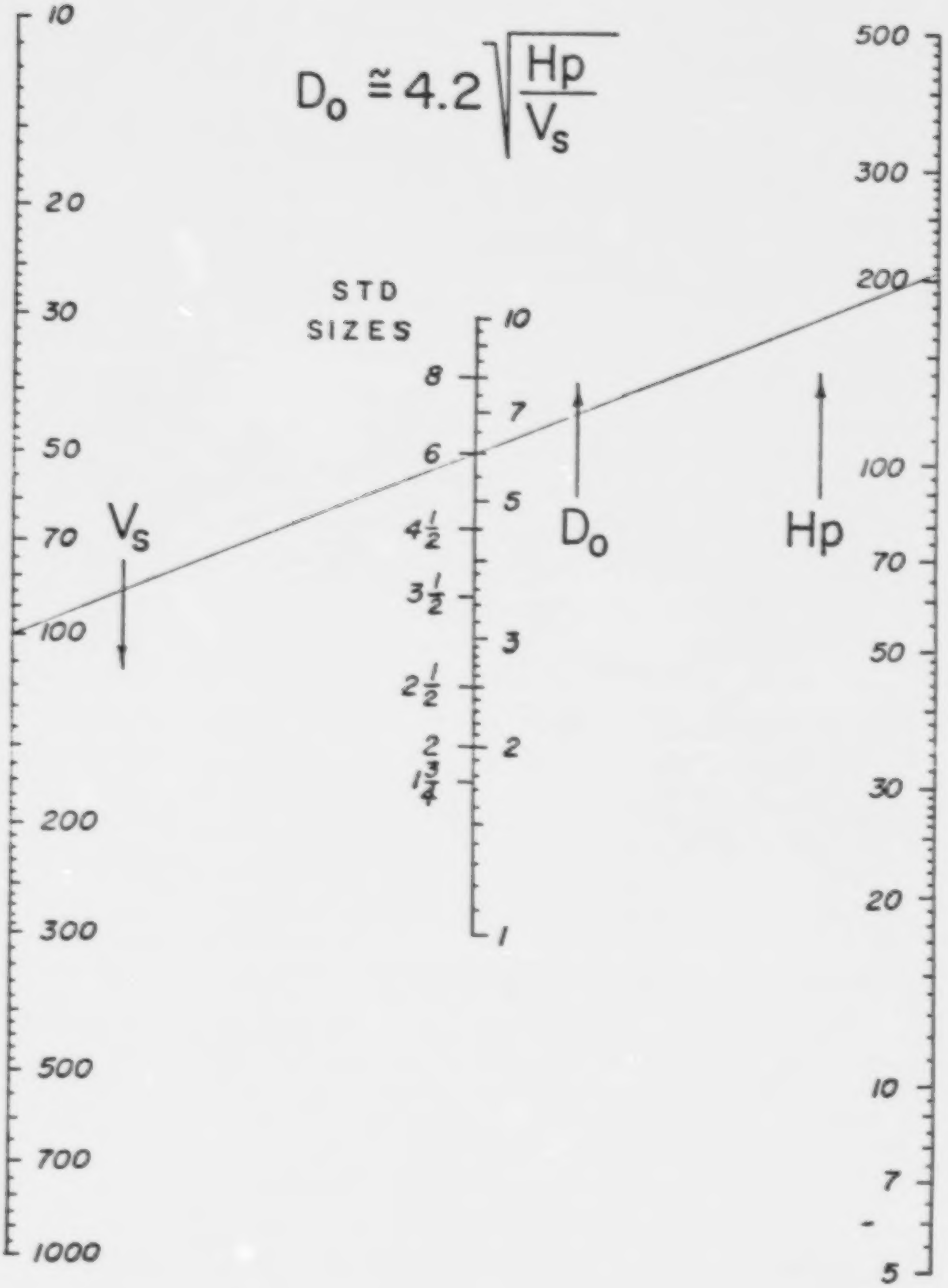
exceed 100-150 ft/min, while for several highly viscous and heat-sensitive materials - rigid vinyl, ABS polymers, acrylics, and very high-molecular-weight polyethylene compounds - the speed should be even lower, from 35 to 65 ft/min.

Since in any power-transmitting shaft, horsepower is proportional to the product of torque and rotational (angular) speed, and since surface speed is just angular speed times shaft radius, the maximum torque for the screw is fixed once the horsepower and surface speed are known. But torque in turn depends on the allowable working stress in the shaft and the cube of shaft diameter. If we put all this together and further assume that the root diameter is not likely to be less than 60% of the nominal and that a reasonable working shear stress limit for high-strength steel is one-third of the shear yield strength, it is possible to calculate a near-minimum nominal screw diameter for the horsepower and surface speed already found. The relationship is given in the nomogram II.

It should be emphasized that these values are based on experience, mostly with one type of extruders, and are thermselves rough values. It is possible that changes in screw design and compound formulation could raise these speeds levels in the future, so the numerical scale for surface speed is extended to 1000 ft/min.

TORQUE LIMITATIONS

The nomogram on page 9 set a minimum value on the horsepower needed for any particular output rate and final melt temperature. But obviously we cannot apply unlimited horsepower to screws without twisting them off. Horsepower, at the screw shank, is really the product of twisting moment, or torque, multiplied by the rotational speed of the screw. Therefore, the higher the speed, the lower the torque needed for a given power input to the screw. Conversely, at low speeds, high torques are needed for high power inputs.



$$D_o \cong 4.2\sqrt{\frac{Hp}{V_s}}$$

II

D_o = SCREW DIAMETER, inch V_s = SURFACE SPEED, FT/MIN

H_p = MOTOR HORSEPOWER

But as the torque, increases, there comes a point where the stength of the screw is exceeded and it shears off. Since the twist on the screw accumulates from the output end to the feed end, the danger of shearing is greatest in the flights near the feed end of the screw, where the entire accumulated torque must be borne and where the metal diameter is usually the least. In the last analysis, it is the metal strength and the screw-root diameter that limit the amount of torque that can safely be applied to the screw shaft. To summarize: for given horsepower, the slower the screw speed, the bigger must be the shaft.

Now let us look at screw speed. At the present time, the speed is limited, in most commercial operations, by the risk of overheating the plastic, with consequent degradation. Also, there is evidence to indicate that as speed goes up, extrudate uniformity and dimensional control suffer. Practical experience in many modern installations indicates that at the present time the speed of screws is limited to roughly 100-150 ft/min at their outer surfaces. Since surface speed is proportional to screw diameter multiplied by rotational speed, larger screws must turn more slowly to meet the 100-150 ft/min limitation. As we noted above, lower speed means higher torque for any given horsepower. Fortunately, the torque that a given screw can carry goes up in proportion to the third power, or cube, of the root diameter, so a 4-inch shaft can carry eight times the torque of a 2-inch shaft made of the same metal. At present screw-speed ranges, therefore, the torque limitation is most serious in the smaller machines.

Thus, over-powering the screw leads either to burning the plastic at too-high speeds or shearing off the screw at too-low speeds. The most meaningful way to express this torque limitation is in terms of the permissible horsepower per 100 rpm of screw speed. Such values are tabulated below for standard screw diameters.

Screw diameter, Inches	1¾	2	2½	3½	4½	6	8	10
Drive Horsepower per 100 rpm Screw Speed	5	10	20	60	120	210	550	800

TYPE OF MOTOR AND REDUCER

Most extruders have a variable speed adjustment and generally a constant torque drive motor. The two main drive systems are electric and hydraulic drives. Electric motors are most common on extruders, either direct current (DC) or alternating current (AC) motors.

Direct current motors allow for speed variation over a wide range, up to 100/1. The speed of dc shunt-wound motors is practically independent of the load. This makes them attractive for extruders. The motor speed can be changed by varying the armature voltage or the field excitation. The wide-speed range allows direct coupling of motor to gear box, eliminating the need for a variable speed transmission.

Alternating current motors have a limited speed range. Again a shunt characteristic is desired in extruder applications. One type of motor where the motor speed is fairly independent of the load is the three-phase squirrel-cage induction motor. Momentary peak loads can be reduced by automatic star-delta switching. Speed control is minimal; these motors are commonly considered to be constant speed motors.

Another AC motor is the shunt-wound commutator motor. By adjusting the brushes, a moderate amount of speed control can be obtained, about 4/1. These motors are used on many foreign extruders. Eddy-current drives are, or rather were, often used in the U.S. These are constant speed AC motors connected with a direct induction coupling. The power transmitted through the coupling increases as the speed difference between the driver and the follower increases. The transmitted torque can be preset. On larger drive units (over 50 hp) the induction coupling is usually water cooled.

Hydraulic drives have the advantage of being adjustable over a wide speed range. The main components are hydraulic positive displacement pump driven at constant speed and a hydraulic motor. Speed control by adjusting the delivery rate of the pump results in a constant torque characteristic. Speed adjustment through the hydraulic motor results in a constant power characteristic.

As mentioned before, one important characteristic of most extruder drives is a near constant torque, independent of speed and motor load. This results in pretty much a linear power versus speed characteristic. It is important to realize what practical implications this has. This means that a motor rated for 50 hp can be overloaded at 25 hp. The full motor power is only available at the maximum speed. At half the maximum speed only half the motor power is available. At one fourth of the maximum speed only one fourth of the motor power is available. Thus, at 25 hp motor load, the motor would be overloaded if the speed was less than half the maximum speed.

If throughput limitations are encountered caused by motor power, it will be worthwhile to check if the motor operates at or near maximum speed. If it is not, then extra motor power will become available if the maximum speed can be obtained. This could be achieved by changing the reduction ratio. For most single screw extruders the specific mechanical energy consumption is around 0.1 hphr/lb. This means that an extrusion rate of 200 lb/hr requires about 20 hp available motor power.

Electric motors usually run too fast to be connected directly to the extruder screw. Most extruders run at screw speeds between 10 to 150 rpm. Therefore, gearboxes are generally placed between the motor and extruder screw. The gear ratio usually ranges from 15:1 to 20:1.

Most gear boxes have multi-step reduction, often a two step reduction. The types of gears that are used are spur, worm, and chain.

A type of spur gear used often in high quality transmissions is the herringbone gear. This type of gear centers automatically, avoids axial loads, and has a high efficiency. Worm reductions are realtively cheap and compact but the efficiency is not very high. Chain reductions use a roller chain and two sprockets of different diameter. They are cheap, not very reliable and not suitable for high reduction ratios.

Gear boxes can be designed with a "quick change gear" feature. This allows rapid changing of the reduction ratio by replacing a set of gears designed for easy access and exchange. If occasional changes in reduction ratio need to be made, a quick change gear option can be very useful. It will save labor and down time and will probably pay for itself quickly. Sometimes the motor and reducer are not directly coupled, but connected with belts and sheaves. In these cases a change in the total reduction ratio can be obtained from a change in sheave diameter. Any change inreduction ratio should be preceeded by a careful check of the power capability of the motor, the power transmission capability, and the power requirements of the polymer.

The thrust bearing assembly is located between the reducer and screw shank. It has to absorb the axial forces generated by the pressure created by the screw at its delivery end. The thrust assembly is usually a combination of a thrust bearing and two radial bearings. High quality thrust bearings are generally self centering tapered roller bearings. Thrust assemblies are commonly designed with a large safety factor. In normal operation- with reasonable diehead pressures of 1000 to 4000 psi- the thrust bearing will last for many years.

The coupling between screw and gear box is often by means of key and slot. A better method is a coupling sleeve with axial splines. This allows a better distribution fo the torque over the full circumference of the screw shank. Some extruders use flexible coupling between screw and reducer.

In twin screw extruders, there is a space limitation for the thrust bearing imposed by the centerline distance of the two screws. This problem is particularly severe in small diameter twin screw extruders with intermeshing screws. Therefore, complicated designs are usually required in twin screw extruders.

b) Extruder cylinder

The extruder barrel is the housing for the screw and must be designed to withstand extremely high local pressures. Depending on polymers to be run, they are lined with a material that can provide either extreme corrosion resitance or high resistivity to abrasive effects. Barrels generally are normally rated to withstand pressures of 10,000 p.s.i.

A medium carbon alloy steel, usually 4140, is used in most barrel constructions. The 4140 is then lined with a suitable material in a centrifugal casting operation. For extremely corrosive materials like saran, fluoroplastics, and unplasticized PVC, an alloy containing nickel, cobalt, chromium, and molybdenum and traces of other elements is incorporated in the liner. Where extreme corrosivity is not a factor, a ferrous alloy that contains nickel and boron is incorporated. After honing, the liner thickness is about 1/16 in. - see Table 3.

Barrels for the most part are smooth throughout their entire length. With materials that are difficult to feed, conveying rates have been improved by incorporating a rifling or grooving in the feed section. The impact of this action is to cause an increase in the friction between the barrel wall and the material, which translates into improved feeding characteristics.

TABLE 3

CYLINDER & LINING - TYPE OF METALS ALLOYS

THERMOPLASTICS	XALOY 101	XALOY 306	XALOY 800*
1. Acrylonitrile-Butadiene Styrene (ABS)	X	X	
2. Acrylonitrile Styrene Copolymer	X	X	
3. Acrylic	X		
4. Carboxymethyl Cellulose (CMC)	X		
5 Cellulose Acetate (CA)	X		
6 Cellulose Acetate Butyrate(CAB)		X	
7. Cellulose Acetate Propionate (CAP)	X		
8. Cellulose Propionate	X		
9. Chlorinated Polyether		X	
10 Cellulose Nitrate-Pyroxylin		X	
11. Ethyl Cellulose (EC)	X		
12. Ethyl Vinyl Acetate Copolymer (EVA)		X	
13. Fluorocarbon		X	
14. Polytetrafluoroethylene (TFE)		X	
15. Fluorinated Ethylene Propylene (FEP copolymer)		X	
15. Polymonochlortrifluoroethylene (CTFE)		X	
17. Vinylidene Fluoride		X	
18. Methylmethacrylate	X		
19. Polyacrylonitrile (PAN)		X	
20. Polyamides	X	X	
21. Nylon 6	X	X	
22. Nylon 6/6	X	X	
23. Nylon 6/10	X	X	
24 Nylon 8	X	X	
25. Nylon 11	X	X	
26 Nylon C-12	X	X	
27. Polybutadiene-Acrylonitrile (PBAN)		X	
28 Polybutadiene-Styrene (PBS)	X		
29 Polycarbonate (PC)	X	X	
30. Polyethylene (PE). low density	X		
31. Polyethylene (PE). medium density	X		
32. Polyethylene (PE). high density	X		
33. Polyphenylene Oxide (PPO. modified)	X		
34. Polysulfone (modified)	X		
35. Polyarysulfone	X		
36. Polybutadiene-Acrylonitrile (PBAN)	X		
37. Polybutadiene-Styrene (PBS)	X		
38. Polyaryl Ether	X		
39. Polyethylene Terephthalate (PET. glass filled)	X		
40 Acrylonitrile-Butadiene-Styrene (ABS. flame retardant)	X		
41. Polyester (Mylar)	X		
42 Poly Hexamethylene Adipamide (Nylon 66)		X	
43. Polyimide	X		
44. Poly Methyl-a-chloroacrylate (PMMA)		X	
45 Polyphenylene Oxide (PPO)		X	
46. Polypropylene (PP)		X	
47. Polystyrene (PS) (unfilled)	X		
48 Polystyrene (PS) 30 35% Glass Fibre Filled General Purpose Type	X		
49 Polysulfone		X	
50. Polyvinyl Acetate (PVAC)		X	
51 Polyvinyl Alcohol (PVAL)		X	
52. Polyvinyl Butyral (PVB)		X	
53 Polyvinyl Chloride (PVC)		X	
54. Polyvinyl Chloride Acetate (PVCAc)		X	
55. Polyvinyl Dichloride		X	
56. Polyvinyl Formal (PVF)		X	
57. Polyvinylidene Chloride		X	
58 Silicone		X	
59 Styrene-Acrylonitrile (SAN)	X		
60 Styrene-Butadiene (SPB)	X		
61 Urethane	X		

*XALOY® 800 is recommended in any molding application where filled plastics are being used.

Xaloy 101 = iron base alloy - hardness 58-64RC

Xaloy 306 = nickel cobalt chrome alloy

Xaloy 800 = tungsten carbide particles dispersed in nickel alloy matrix

If devolatilization is required, the extruder barrel can be ported in desired places and vacuum applied in this section. Venting or porting is useful in improving extrudates of hydroscopic materials or with polymers possessing residual monomer or a high volatile content.

In addition to barrels fabricated with the centrifugal cast-type liners, there are some made solely of 4140 steel which in turn is nitrided. Nitriding provides for only case or skin hardening which is basically inferior to the alloy liners and has only limited utility.

c) Screw construction

First, a screw must be able to withstand strong rotational forces. These forces are considerable since the screw is rotated from one end only to force plastic material forward in the cylinder. This winds the screw up like a spring and requires a tough piece of steel with good elasticity. The flight surfaces, however, are constantly rubbing the barrel's inside surface and must, therefore, have a very hard surface for long wear, mostly special high alloy steels. A forged bar is turned and ground on the outside diameter. If the screw is to be cooled, it is gun drilled through the center. The contour is then milled leaving the required flights. The shank is machined as required. Finally, the flights are flame hardened and the screw is ground and polished. Flame hardening hardens the top of the flights to 55-56 Rc to a depth of about .015". Once this thin surface wears off, the screw will deteriorate rapidly producing fewer and fewer pounds because of the resulting backflow of polymer. Stelliting flights is one way to extend screw life. Here we weld a hard metal alloy on to the wear surface and grind it to proper dimensions. It is 25% more expensive but will last 3 or more times as long. Screw suppliers offer different hard surface treatments as shown on Tables 4 and 5. For lines that run PVC and other corrosive materials, plating the extruder screw is a must. Chrome plating is the standard process because it is easy to clean and resists corrosion well. However, there is increasing discussion that nickel

Table 4 — Materials Of Construction For Screws

Material	Finished Flight Hardness	Base Material Hardness	Base Tensile Strength	Resistance to Abras	Resistance to Corro	Comments
Carbon steels						
4140	50-55 Rc	28-32 Rc	150,000	Poor	Poor	Principal screw material used in U S
4340		38-42 Rc	180,000	Poor	Poor	Used in place of 4140 for high torsion strength
1020		79 Rb	69,000	Poor	Poor	Used only with hard faced flights, where low torsion strength required
1035		90 Rb	85,000	Poor	Poor	
4130		90 Rb	85,000	Poor	Poor	
Nitrided steels						
Nitralloy 135M	65 Rc	30 Rc	145,000	Good	Fair	Subsitute for 4140 flame hardened Offers hardness on root as well as flight lands for abrasive applications
4140	50 Rc	30 Rc	150,000	Fair	Poor-Fair	
Tool steels						Provides high torsion strength and good abrasion resist on full surface area Limited to smaller sizes
D 2	64 Rc	64 Rc	240,000	Good	Poor	
H 13	51 Rc	51 Rc	260,000	Good	Poor	
Stainless steels						
304		81 Rb	170,000	Poor	Fair-Good	Used almost exclusively in corrosion resist applications in FDA certified processing Hard surfaced in all plastics applications
316		78 Rb	118,000	Poor	Good	
17-4 PH		38 Rc	170,000	Fair	Good	
Duranickel						Good resist to hot HF and other acids Most screws are hard surfaced
301		32-42 Rc	180,000	Poor	Excel	
Hastelloy						Excellent corrosion resist to almost all chemicals and environments Most screws are hard surfaced
C 276		94 Rb	134,000	Poor	Excel	

Table 5 — Materials For Abrasion Or Corrosion Protection Of Screws

Material	Finished Flight Hardness	Base Material Hardness	Base Tensile Strength	Resistance to Abras	Resistance to Corro.	Comments
Cobalt base						
Stellite 6	49 Rc*	37 Rc	105,000	Good-Excel	Good	Widely used hard facing for abrasion resist Can be applied to most screw materials
Stellite 12	50 Rc*	41 Rc	76,000	Good-Excel.	Good	
Stellite 1	48 Rc	48 Rc	47,000	Good-Excel.	Good	
Nickel base colmonoy						
56	50-55 Rc	50-55 Rc	45,000	Good-Excel	Good-Excel	Provides excellent abrasion resist and resists galling Application to carbon steel base results in some cracking
5	45-50 Rc	45-50 Rc		Good	Good-Excel	
6	56-61 Rc	56-61 Rc	30,000	Excel	Good-Excel	
Bimetallic coatings						
UCAR WT-1	70 Rc	N/A	N/A	Excel	Poor	Provides excellent abrasion resist, can be applied to all screw materials
Nye Carb	60-65 Rc	N/A	N/A	Excel	Good	
Ceramic coatings						
Chrome oxide	80 Rc	N/A	N/A	Excel.	Poor	Most abrasion resist materials currently used Coatings are fragile.
Aluminum oxide	80 Rc	N/A	N/A	Excel.	Poor	
Chrome plating						
Hard chrome	70-72 Rc	N/A	N/A	Good-Excel.	Good	Used mostly for corrosion resist. If applied in suitable thickness, offers abrasion resist.
Nickel plating						
Electroless nickel	45-50 Rc	N/A	N/A	Poor-Fair	Excel.	Can be applied more evenly than chrome.

plating may be a better solution. Although chrome has good hardness, it is subject to intergranular cracking which allows corrosion underneath the plating surface and lifts the chrome off. By heat treating a nickel plated surface, it can be made almost as hard and the corrosion resistance is superior. Nickel is also less brittle and hence less likely to crack when the screw is subjected to loading.

c1) Screw design

Figure 4 defines the terminology used to describe on extruder screw. The screw design is the largest factor responsible for delivering fully melted, mixed polymer, at a uniform temperature- cross-bore and machine direction- and at a uniform output rate (usually judged by steady pressure level).

Today's standards for extruder output and extrudate quality are so highly advanced that no longer can one screw design be optimum for all materials and extrusion products.

Yet, every screw design is a compromise. Some of the factors which fight each other in this compromise are:

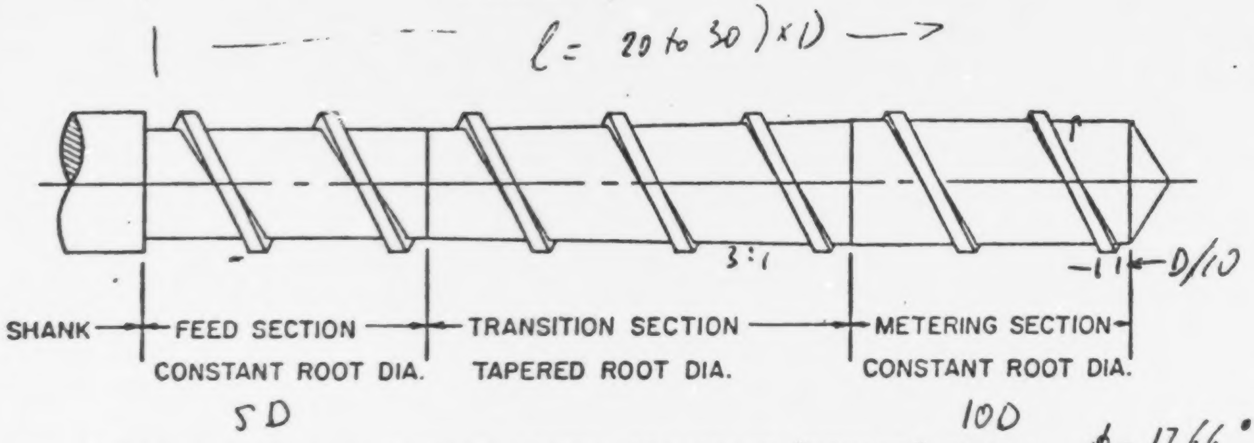
- More output at a lower temperature usually dictates a deeper screw; this yields poorer stability, less pressure pumping capability and less mixing or refinement of the polymer.

- More output usually dictates more speed (RPM), but this almost inevitably equates to a higher melt temperature, which often has adverse effects on both processability and finished part properties.

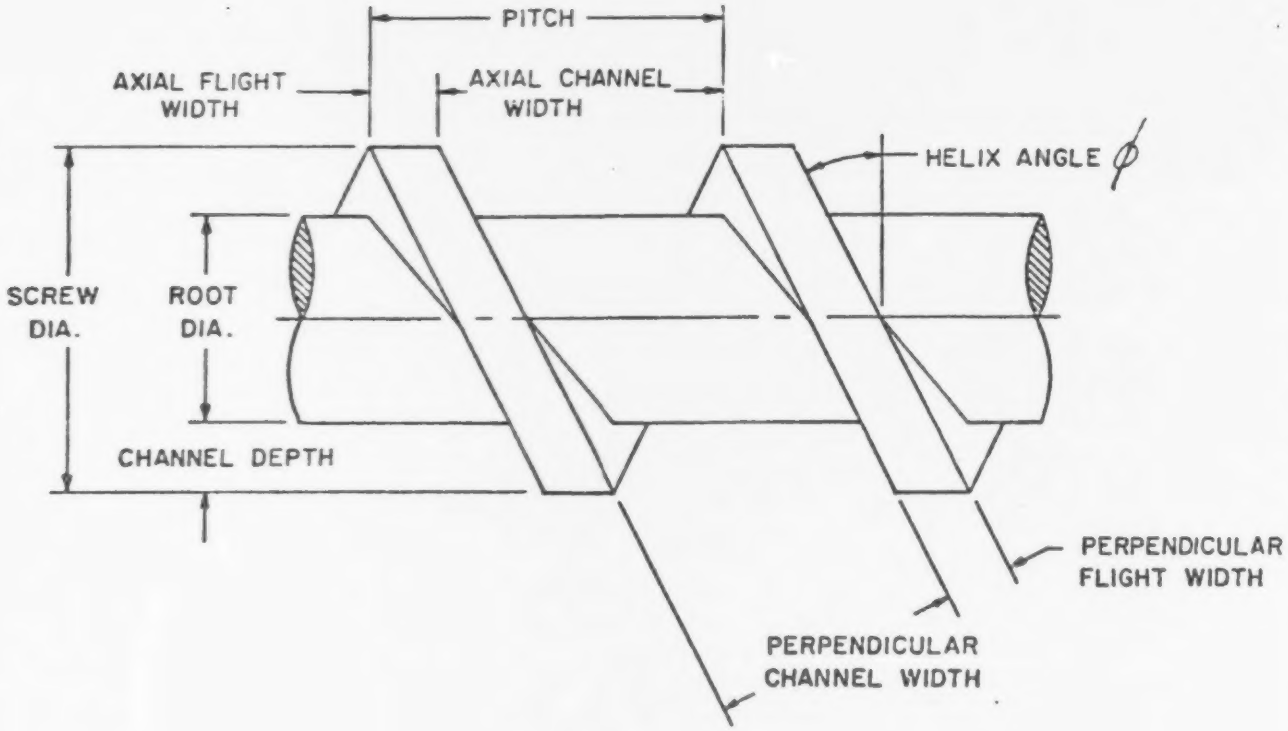
- A longer screw yields greater output and melt homogenization, but usually raises melt temperature.

- While it is often desirable to remove excess melt heat in the metering section of the screw (through the barrel walls and

FIGURE 4


l = 20 to 30)×D
3:1
D/10
SHANK
FEED SECTION
TRANSITION SECTION
METERING SECTION
CONSTANT ROOT DIA.
TAPERED ROOT DIA.
CONSTANT ROOT DIA.
5D
10D

CONVENTIONAL SINGLE STAGE SCREW (CONSTANT "SQUARE" PITCH) $\phi = 17.66°$


PITCH
AXIAL FLIGHT WIDTH
AXIAL CHANNEL WIDTH
HELIX ANGLE φ
SCREW DIA.
ROOT DIA.
CHANNEL DEPTH
PERPENDICULAR FLIGHT WIDTH
PERPENDICULAR CHANNEL WIDTH

IMPORTANT TERMS IN DEFINING SCREW GEOMETRY heater/coolers), this tends to increase cross-bore temperature variation.

The common generic types of screws in use today are:

(A) Basic Metering Screw (Fig. 4A).

Used extensively 20 years ago for the extrusion of most materials, this screw design is still utilized in the fiber industry and for the extrusion of PVC compounds.

It has the three zones common to all extrusion screws: a feed zone, a transition zone, and a metering or pumping zone.

The feed zone picks up the resin under the hopper and starts it into the externally heated barrel to begin polymer melting.

The transition zone compresses the material, eliminating air pockets and establishing a solid bed of unmelted pellets or powder with melt filling all voids. Much of the conversion of mechanical energy of the drive to heat occurs in this section, providing a major source of energy needed to melt the polymer.

The metering or pumping section of the screw generates the pressure needed to force the polymer through the die system. In the process, the rest of the polymer is melted and refined into a homogeneous mass.

(B) Maddock (Union Carbide Corp.) Mixing Type Screw (Fig. 4B).

This screw has become the workhorse of the polyethylene film industry. It refines the polymer through one close-clearance shear point to remove gels and fish-eyes, and yet yields a relatively high output of melt at a low stock temperature.

The UCC-Maddock section is usually located about 2-4 diameters to the rear of the tip of the screw to place it in an area of the barrel subject to the temperature control of heater/coolers and to provide some pumping capability beyond the mixing section.

(C) Pin Mixing Screw (Fig. 4C).

Heavily developed and optimized by Davis-Standard, this screw's mixing action differs from the UCC-Maddock in that the multiple rows of pins break up the channel circularoty pattern repeatedly under low shear conditions, forcing it to reestablish itself in a random manner, rather than having one high shear mixing and homogenizing action. In the usual balance of output, rate degree of melt temperature uniformity, stock temperature and pressure stability, the Davis-Standard Pin and the UCC Maddock mixing screws are quite similar.

If there is a material difference, the Maddock screw may be marginally better at gel reduction, and the Pin Mixing screw may be marginally better in distributive mixing. The advantages of both mixing screws also apply with increasing L/D ratios.

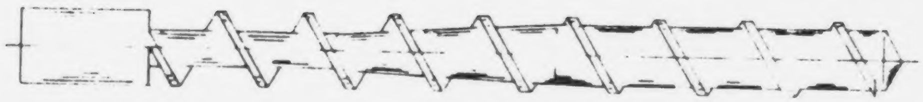
(D) Compression Relief Mixing Screws (Fig. 4D).

Used very successfully in longer (typically 34:1) extruders, the compression relief mixing screw has the feed, transition and meter of the UCC and Pin Mixing Section and offers deep channel low shear pumping, therefore, minimal stock temperature elevation. Further, this design tends to operate at a higher volumetric efficiency, as the first stage meter always pumps against a moderate (500-1500 PSI) pressure, not the usually higher (2500-6000 PSI) process head pressure.

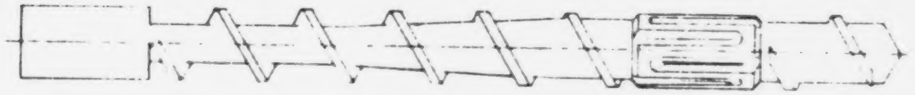
(E) Vented Screw (Fig. 4E).

The classical vented screw has feed, transition and metering sections in the first stage. This first meter dumps into the deep vent area which may be either open to atmosphere or subjected to vaccum. Following the vent section is a recompression section, plus a second metering section, which pumps the polymer against the head or die pressure.

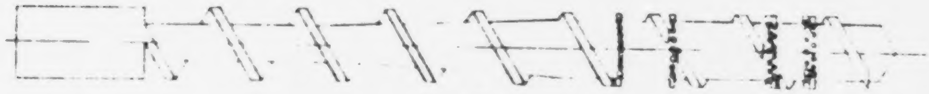
FIGURES 4A – F
SCREW DESIGN



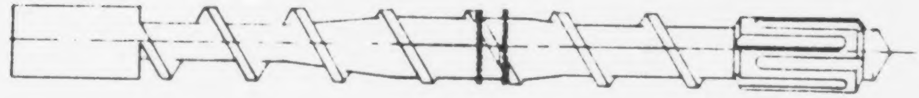
(Fig. A)



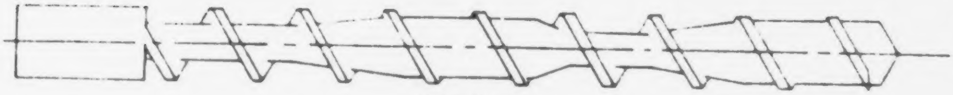
(Fig. B)



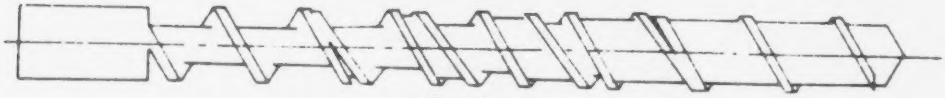
(Fig. C)



(Fig. D)



(Fig. E)



(Fig F)

(F) Barrier Screw (Fig. 4F).

The melt separation or barrier type screw is available in many different designs, one or more of which may approach pressure optimum for your extrusion process.

These designs normally have two channels, a melt channel and a solids channel, which are separated by a secondary or barrier flight. The height of the barrier flight is less than that of the primary flight. As a result, melt is scraped off the barrel wall only by the primary flight and is collected in the melt channel, located between the leading edge of the primary flight and the barrier flight. In a well-designed barrier screw, the volume of the melt channel increases at a rate at least equal to the melting rate of the polymer which assures that not melt will collect in the solids channel. The increase in volume is accomplished either by deepening or widening the melt channel, or a combination of the two. In a reverse manner, the volume of the solids channel is decreased as the end of the melting section is approached. This design provides a highly efficient melting mechanism, resulting in high output rates with exceptional pressure stability.

There is no one "universal" screw design. The screw designs that have evolved as "best" for a particular industry or application are largely a function of compromises that application can accept in trading off output, melt temperature, mixing and output uniformity while still meeting customer end product performance requirements. This evolutionary process will continue as resins, markets and property requirements change, and as new screw configurations are conceived and put into use.

d) Instrumentation

The extruder barrel is equiped with heating and cooling systems to maintain a particular temperature profile along the barrel. Barrel heating consists usually of electrical resistance heaters clamped around the length of the barrel. They are usually grouped in 3 to 6 zones.

Each zone having a separate thermocouple and temperature controller, thus allowing independent temperature control for each zone. The maximum specific heating capacity or resistance heaters is about 40 watts/inch ^{2}.

Cooling can be done with either air or water. Air cooling is usually done with blowers. The cooling system is generally divided into zones, such that each zone can be cooled independently. The cooling zones normally coincide with the heating zones. Water cooling is more effective than air cooling in terms of heat removal. However, smooth temperature control may be more difficult with water cooling.

Systems for heating and/or cooling of the extruder screw are not as common as they are for the extruder barrel. However, a screw heating or cooling capability can be added relatively easily. The heat transfer medium (water, oil, etc) enters the hollow screw core and runs thru a pipe to the end of the bore. The connection between screw and supply lines can be made with a rotary union to keep the system closed. It is also possible to stick a pipe into the screw core and drain back into the open at the end of the screw. Obviously, the alter method provides a very simple method of screw temperature control. Provisions can be made to heat or cool only particular sections of the extruder screw. Electrical cartridge heaters have also been used for screw heating.

In some cases screw cooling is used to compensate for a screw cut too deeply. The effective channel depth is reduced by solidification of a layer of material on the screw surface. This mode of operation is not recommended since it wastes energy and means that an improper screw design is used. It could also widen the residence time distribution and cause degradation problems in heat sensitive materials. Screw cooling can also be used to reduce surging of the extruder.

When considering the heating and cooling requirements of an extruder it is important to take into account the size of the extruder. For small extruders the cooling requirements are less severe than with larger extruders. The surface area to channel volume ratio is large for small extruders. Thus cooling through conduction and radiation can be considerable. Temperature control, therefore, becomes more difficult as the extruder size increases.

d1) Controllers

Instrumentation is the most crucial element of the extruder components for process control and trouble shooting. The internal workings of the extruder are totally obscured by the barrel and die. The only visual observation that can be made is the extrudate leaving the die. Thus, fo find out what is happening in the extruder we need good instrumentation. With the instrumentation the "vital signs" of the extruder can be monitored. The vital signs are pressure, temperature, power, and speed.

A complete set of instrumentation should include:

1. diehead pressure before and after screen pack
2. rotational speed of the screw
3. melt temperature reading(s) at the die
4. power consumption of the extruder drive
5. power consumption of each barrel heater or heat zone
6. temperature readings along the barrel and die
7. with water cooling; flow rate and water temperature rise.

Good instrumentation allows small problems to be detected early before becoming more severe, allows a high degree of process control, allows production of more uniform and more consistent extrudate, in case of a problem allows logical step by step trouble shooting, allows process characterization for process development and optimization, for production control and records, allows for computer interface, etc.

It is clear that there are many sound reasons for equiping an extruder with good instrumentation. Unfortunately, this is often forgotten in the process of preparing purchase specifications for new extruders. There is also a tendency to save money by skimping on instrumentation. However, insufficient or inadequate instrumentation can create very costly production problems that totally overshadow any amount of money saved on instrumentation.

On the subject of process control a brief discussion on temperature control is in order. Good temperature control is very important for steady extrusion. Many extrusion problems are caused by problems in the temperature control system. Three main types of control systems are manual control, on/off control, and proportional control.

Manual control is the cheapest an simplest control system. The amount of heat applied is varied with visual observation of the actual temperature. Variation of applied heat can be with a potentiometer or variable transformer (Variac, Trafo) or by impulse control. The accuracy of this method of control is highly dependent on the reliability of the personnel.

On/off was the first type of automatic temperature control. This type of controller compares the measured temperature with the temperature setpoint and simply switches off the power supply to the heater when the setpoint is exceeded. The control characteristics of such a system are shown in figure 5. Under steady state conditions the temperature will cycle about the setpoint. The magnitude of the cycle will depend on the temperature lag between thermocouple and heater. The location and depth of the thermocouple are important parameters affecting this thermal lag. In general the temperature excursions above and below the setpoint are large, making on/off control undesirable for situations where very close temperature control is required.

Proportional controllers apply an amount of power to the heater that is proportional to the measured temperature. The first systems were time proportioning control systems. In these systems the "on" time is varied to control the power applied to the heater. This is basically a variable frequency on/off control. If the power switching cycle is considerably shorter than the natural cycle time, the temperature oscillation will die away and the temperature will stabilize at a steady value.

The time proportioning system was improved with the introduction of SCR'S (silicon controlled rectifiers) which proportioned a constant but smaller amount of power to the heaters. The proportional band is the temperature band in which power is proportioned to the heater. The setpoint is normally the upper limit of the band, at this point the heater input power is zero. The lower limit represents full power applied to the heater. If power is required to maintain the setpoint temperature, the actual temperature will be lower than the setpoint. This is the off-set or droop error. The offset error can be reduced by decreasing the proportional band. However, this will increase the initial temperature overshoot on start up. It will also adversely affect the damping of the oscillations after start up. The control characteristics of the proportional-only control is shown in figure 6.

A disadvantage of the proportional-only controller is that it is based on steady state conditions. An upset in the thermal balance of the system will require a correction of the amount of power applied to the heater to maintain the same temperature. In an extruder a change in throughput or a change in resin viscosity would cause a change in thermal balance. A proportional-only (P) controller is incapable or correcting for a change in the thermal balance. This can be a problem if frequent changes in operating condition and/or polymer properties occur.

To circumvent this problem an automatic reset can be incorporated in the control circuit. This feature automatically eliminates the process droop. An electronic circuit picks up a possible change in

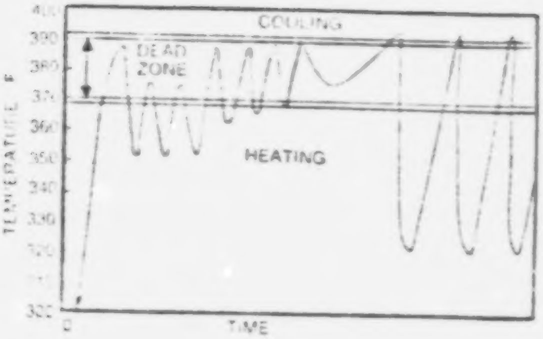


Figure 5 Temperature curve for extruder barrel with on off control from startup to steady-state operation.

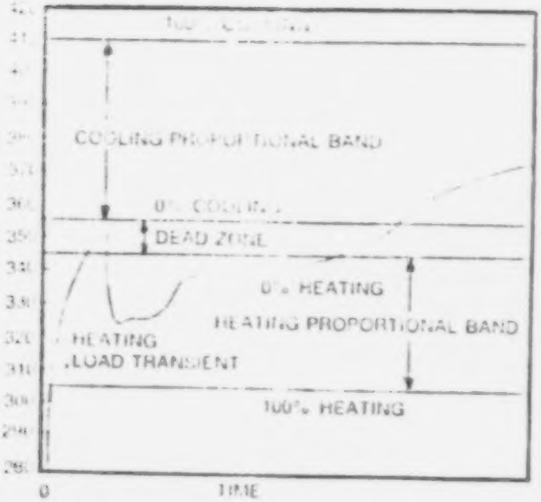


Figure 6 Temperature curve for extruder barrel with proportional control. After initial overshoot at startup, temperature attempts to stabilize within the heating proportional band until the heat generated by the screw eventually causes the temperature to climb into the cooling band.

steady state conditions and adjusts the controller output to maintain setpoint conditions. The reset function includes adjustments which allow it to handle systems with widely varying characteristics. An illustration of the proportioanl and reset controller is shown on figure 7.

Proportional control can be combined with rate or derivative control to eliminate large overshoots normally encountered during start up. This can be particularly severe when the time constant of the process is long, as it is in extrusion. An electronic circuit senses the rate of change in process temperature (the derivative of temperature with time) and produces a signal proportional to the rate of change. Thus, corrective action can be taken before the temperature variation becomes excessive. Proportional plus derivative (PD) control allows a narrow proportional band reducing the offset error and improving control.

Proportional plus integral plus derivative (PID) control is used to automatically eliminate the offset error. This is achieved by integrating the error signal to provide a power control signal that reduces the error progressively to zero. Thus the effect of the integrator is the same as manual trimming. The PID controller is capable of holding the setpoint without hysteresis; this is possible because of the sluggish response of the integrator (Fig. 8).

Controlling the extrusion process temperature may require cooling instead of heating. Particularly at high screw speeds and with high viscosities the internal viscous heat generation can be considerable. Thus, it is clear that dual controllers are required capable of controlling both heating and cooling. The requirement for cooling control is at least as stringent as that for heating control.

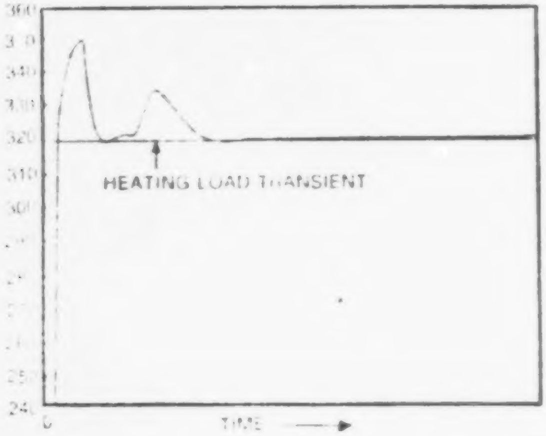


Figure 7 Automatic reset and rate functions in proportional controllers eradicate droop error Reset and rate functions bring sensed temperature to setpoint level from upward swings of startup and heating-load

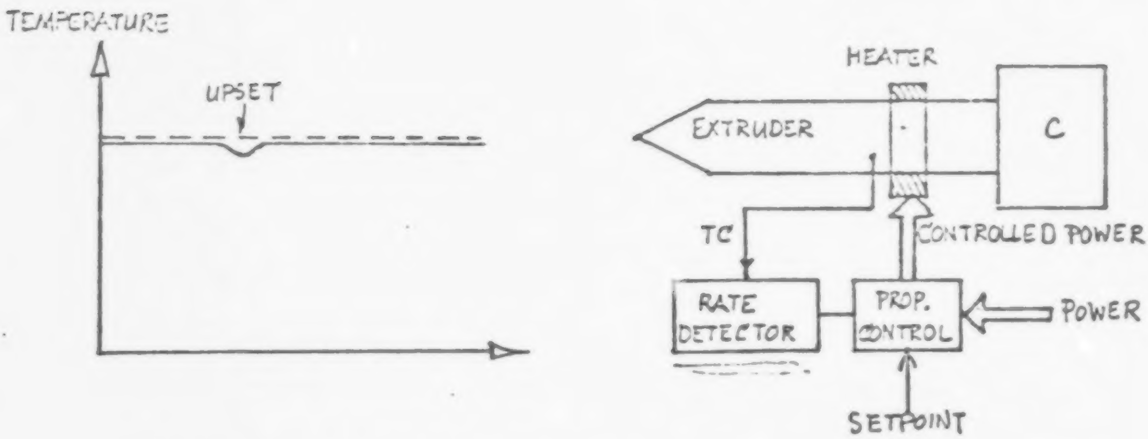

TEMPERATURE
UPSET
HEATER
EXTRUDER
C
TC
CONTROLLED POWER
RATE DETECTOR
PROP. CONTROL
POWER
SETPOINT

FIGURE 8: RESPONSE TO UPSETS FOR VARIOUS PROPORTIONAL CONTROL SYSTEMS

e) Die assembly

The die is usually connected to an adaptor, while the adaptor in turn is connected to the extruder barrel. The purpose of the die is to shape the extrudate. This shape can be the final product shape or an intermadiate shape that is later modified in a post extrusion process step.

Quite often a breaker plate is incorporated between the barrel and the adaptor (see Fig. 9). The breaker plate is a thick circular disk drilled with many holes spaced closely together. The purpose of the breaker plate is to arrest the rotating motion of the extrudate as it is forced from the screw to the die exit. It can also be used to support screens to filter out contamination in the polymer. The screens are placed at the upstream side of the breaker plate. Screens can also be used to intentionally increase the diehead pressure to obtain better mixing.

The die is one of the most important elements in extrusion. Proper die design is essential for producing a quality extrudate. Unfortunately, die design is one of the most complicated aspects of polymer process engineering. It requires a thorough knowledge of the flow characteristics of the polymer and the product requirements. A description of the flow behavior of the polymer in the die usually entails highly complex mathematics unless very simple geometries are involved (see Tables 6 & 7 and Fig. 10).

A good die designer, therefore, should be a good rheologist, mathematician, and a designer. A fundamental approach to die design can present great difficulties. For this reason a largely empirical approach is used for many die designs, particularly for the more complicated geometries. This makes die design more of an art and puts a high value on experience. However, empirical approaches rarely lead to fundamental improvements. One tends to use a design that used to work and make

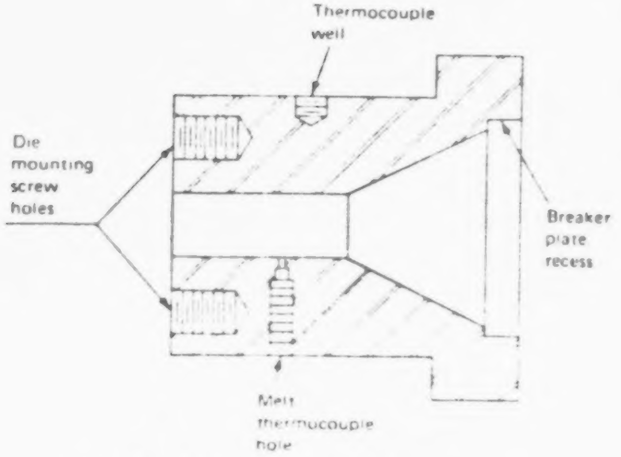
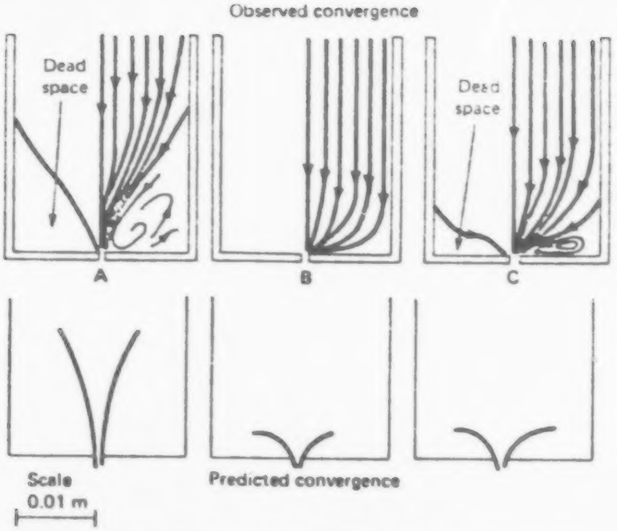

Thermocouple well
Die mounting screw holes
Breaker plate recess
Melt thermocouple hole

Fig. 9 Schematic drawing of typical die adapter


Observed convergence
Dead space
Dead space
A
B
C
Scale
0.01 m
Predicted convergence

A Low density polythene (MFI 2-0) at 190°C (374°F)

B Extrusion grade polypropylene at 230°C (446°F)

C Moulding grade acrylic at 230°C (446°F)

Reprinted from Polymer Engineering & Science 12, 69, Jun. (1972).

Fig. 10 Natural die entry flow profile for several materials at a shear rate of 300 sec^{-1}.

TABLE 6

The general condition for fluid flow through a die is given by the following relation:

$$Q = \frac{\Delta P}{K\eta} \qquad (1)$$

where: Q = volume rate of flow
ΔP = pressure drop across the die
η = fluid viscosity
K = resistance constant

Value of the resistance constant, K, for dies of different configuration are as follows:

$$\text{circular die} \quad K = \frac{128\ (L + 4D)}{\pi D^4} \qquad (2)$$

$$\text{slit die} \quad K = \frac{12L}{Wt^3} \qquad (3)$$

$$\text{tubular die} \quad K = \frac{12L}{C_m t^3} \qquad (4)$$

where: D = diameter, circular die
L = land length
W = die width, slit die
t = die opening, slit die
t = wall thickness, tubular die
C_m = mean circumference, tubular die

TABLE 7

Flow Equations May Help Predict Correct Land Length of Die

The proper land length in the die permits streamlining and balanced flow of material in the die. According to engineers at B. F. Goodrich Chemical Co., the proper land length can be estimated by finding first the shear rate and then the pressure drop at the die lips for a particular profile. Using raw material data that can be provided by the materials supplier, the following rheological equations have been devised for the computation of the land length that would be desirable in dies for profile slits, rods, and tear-drop shapes that are used in sheet dies:

SLIT

$$\text{Shear Rate, sec}^{-1} = 4.61 \times 10^{-2} \times \frac{\text{Flow, lb/hr}}{(\text{Density, gm/cu cm})\ (\text{Die Width, in.})\ (\text{Slit Thickness, in.}^2)}$$

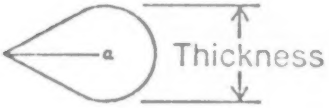
$$\text{Pressure, psi} = 2.9 \times 10^{-5} \times \frac{(\text{Shear Rate, sec}^{-1})\ (\text{Viscosity, poises})\ (\text{Land Length, in.})}{\text{Slit Thickness, in.}}$$

ROD

$$\text{Shear Rate, sec}^{-1} = 9.8 \times 10^{-3} \times \frac{\text{Flow, lb/hr}}{(\text{Density, gm/cu cm})\ (\text{Radius, in.}^3)}$$

$$\text{Pressure, psi} = 2.9 \times 10^{-5} \times \frac{(\text{Shear Rate, sec}^{-1})\ (\text{Viscosity, poises})\ (\text{Land Length, in.})}{\text{Radius, in.}}$$

TEAR DROP



$$\text{Shear Rate, sec}^{-1} = 0.123 \times \frac{\text{Flow, lb/hr}}{(\text{Density, gm/cu cm})\ (\text{Thickness, in.}^3)\left(\frac{\pi}{2} + \frac{1}{\text{Tan }\alpha}\right)}$$

$$\text{Pressure, psi} = 1.45 \times 10^{-5} \times \frac{(\text{Shear Rate, sec}^{1})\ (\text{Viscosity, poises})\ (\text{Land Length, in.})\left(\frac{\pi}{2} - \frac{1}{\text{Sin }\alpha}\right)}{\text{Thickness, in.}}$$

Shear rate, say Goodrich engineers, relates to the dimensions of the die and the profile's opening, the shear increasing as the volumetric-flow rate increases and decreasing as the profile widens; e.g., doubling the width of the profile will halve the shear rate.

Pressure drop, though not important by itself, basically determines the land length and the thickness of the profile, as seen in these equations. By adjusting the measurements of the die lip and the land length, the designer can adjust the amount of the pressure drop, says Goodrich.

A large pressure drop is inevitable in profile extrusion since pressure outside the die is 0 psi, but Goodrich engineers caution that if the pressure in the die is too high, namely over 4000 psi, the high pressures may cause the die to leak or force the material to back up over the screw. Pressures below 4000 psi are considered suitable for PVC profile extrusion.

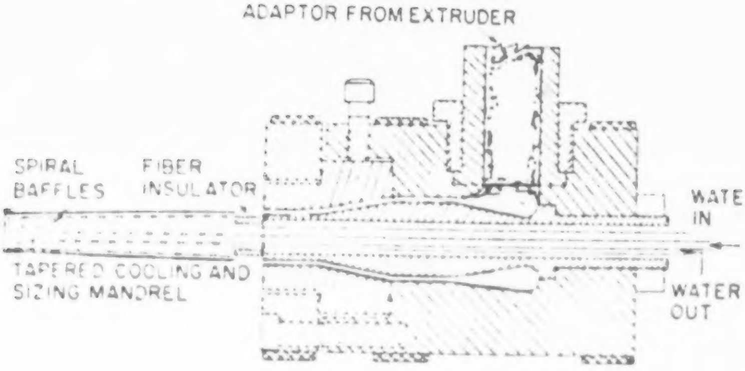

ADAPTOR FROM EXTRUDER
SPIRAL BAFFLES
FIBER INSULATOR
WATE IN
TAPERED COOLING AND SIZING MANDREL
WATER OUT

Fig. 11a. Tubing extrusion die equipped with internal cooling and sizing mandrel

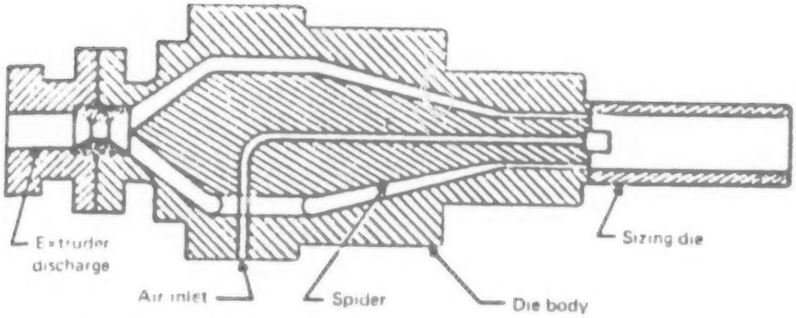

Extruder discharge
Air inlet
Spider
Die body
Sizing die

Fig. 11b Cross section of a typical pipe extrusion die. The long land length minimizes spider line formation.

slight modifications to it. Design rules that work for one material may not hold for another material. Therefore, it is important to understand interaction between material characteristics, die design and operating conditions.

There is an extremely large number of different die designs. They can be categorized by the shape of the extrudate that is produced: annular geometries (pipe and tubing), circular geometries (rod, coated wire, filament, etc), thin rectangular geometries (film and sheet), and finally the more complex geometries.

There is very little difference between a pipe and tubing die. It is mostly a question of size, small diameter products (about 1 cm or less) are called tubing, and pipe if it is larger. Sometimes larger diameter products are called tubing if they are thin walled and flexible. Two typical pipe and tubing dies are shown in figure 11. As the polymer flows thru the die body it has to flow around the legs of the spider support of the core. After the spider support the split streams recombine to a tubular stream. This can cause weld lines in the product and form a weak region that could result in premature failure of the product.

Figure 12, 13 and 14 show several types on sheet dies. The objective of all sheet dies is to deliver a sheet of uniform thickness. To achieve this, the opening of the die can be adjusted by for instance a flex lip adjustment. A choker bar in the center portion of the die provides another means of adjustment. Setting a particular temperature profile across the die is another method of adjustment. There are two general categories of dies used for profiles in terms of general construction. They are plate dies and streamline entry dies as illustrated on Figs. 15, 16 & 17. The first one is used for simple geometry product and short run whereas the second is necessary for high speed and long production run. The die to make a square section is a good one to use to illustrate the die construction required to get good

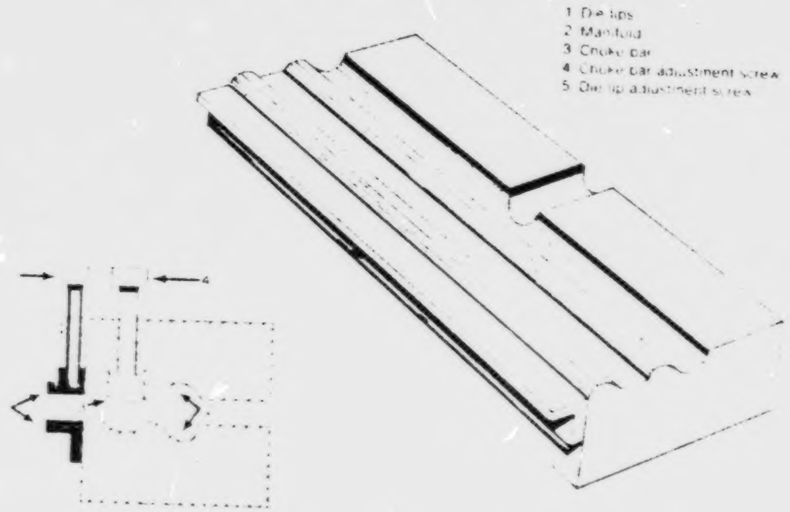

1 Die lips
2 Manifold
3 Choke bar
4 Choke bar adjustment screw
5 Die lip adjustment screw
4
1

Fig. 12 Straight manifold sheet die. Lower half and cross section

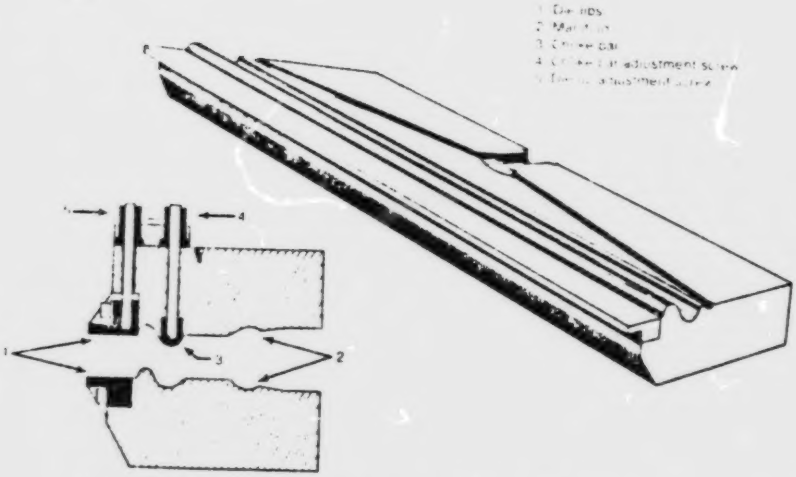
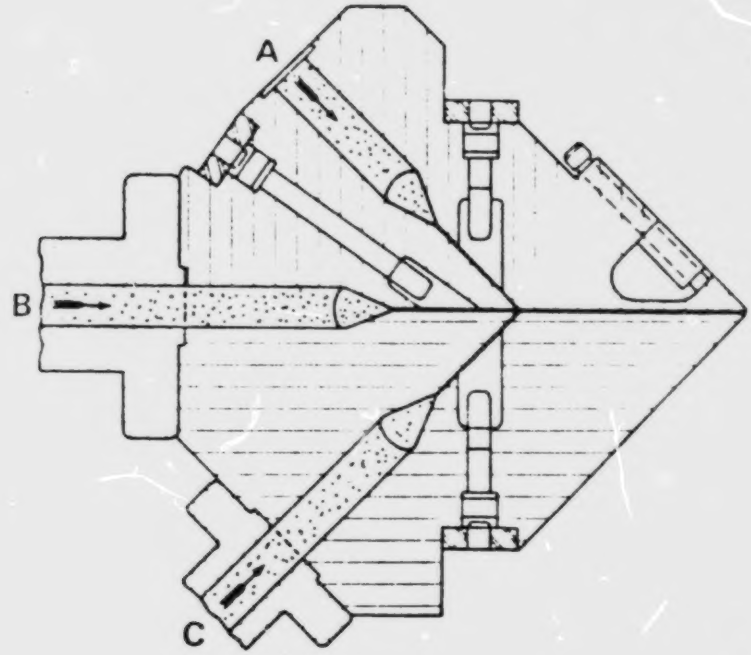
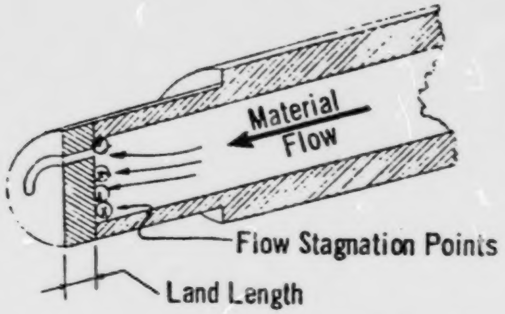

1 Die lips
2 Manifold
3 Choke bar
4 Choke bar adjustment screw
5 Die lip adjustment screw
6
5
4
1
3
2

Fig 13 Coat-hanger manifold sheet die. Lower half and cross section.



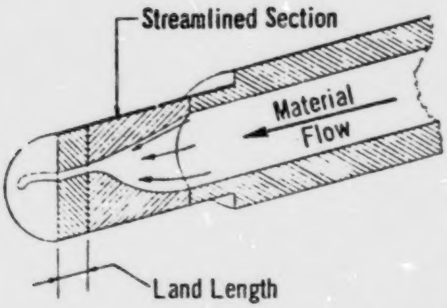
End View

Fig. 14 Coextrusion die with separate manifolds (A, B, C) for each resin.


Material Flow
Flow Stagnation Points
Land Length

Courtesy Tennessee Eastman Co.

Fig. 15 . Plate-type profile extrusion die.


Streamlined Section
Material Flow
Land Length

Courtesy Tennessee Eastman Co.

Fig. 16 Streamline profile extrusion die.

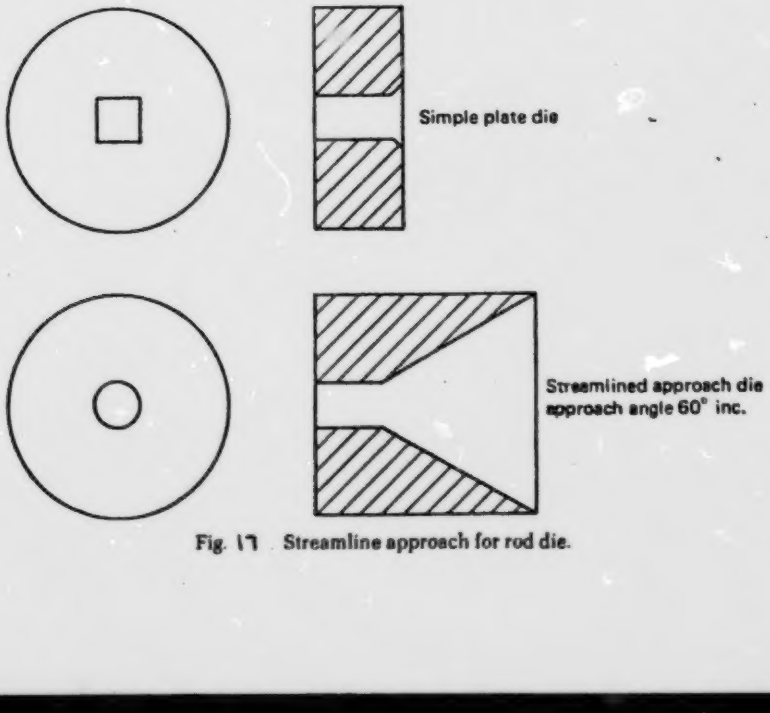

Simple plate die
Streamlined approach die approach angle 60° inc.

Fig. 17 . Streamline approach for rod die.

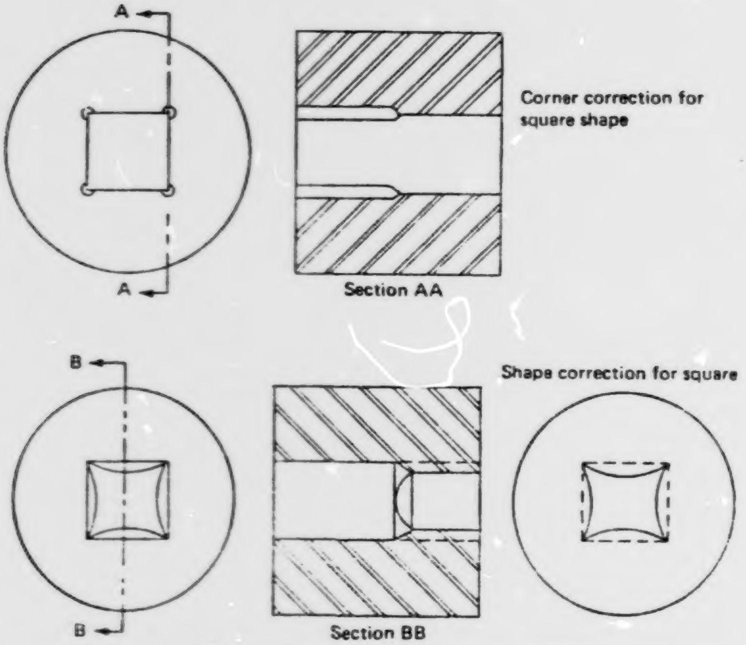

A
Corner correction for square shape
A
Section AA
B
Shape correction for square
B
Section BB

Fig. 18 Shape corrections needed in profile die for square shape.

product shape. The square section is a two-dimensional flow problem which indicates that in addition to flow in the machine direction there is some flow across the extruded section. In some instances the approach section of the tool is a major influence on the profile, and with a simple conical approach, a die with a square opening can produce an essentially round part. The die must be corrected by adjustment of the die channels to make the product square. Figure 18 shows several versions of a die to extrude a square shape.

The upper illustration shows the method of producing a square corner in the part by modification of the channel length, and the lower illustration shows a modification of the channel shape. If neither correction is applied, the part will come out of the die with heavily rounded corners as a result of the extra drag in the corners of the die. By reducing the land length in the corners, the drag is reduced and the corners fill out to make the shape square. The alternative method is to exaggerate the shape by deeepening the corners so that additional material flows in the corners to make the part square.

The two different approaches can make the part but there are substantial differences in operation and correction requirements. In the case of the reshaping of the die it is a cut-and-try approach which depends to a great deal on the experience of the designer and toolmaker as to exactly what the shape must be. In addition, since the materials are very shear-sensitive as to viscosity, the range of operating rates is closely limited to the one for which the corrections were made. In the case of the land length, correction estimates can be made on the length of land removed in the corner based on pressure-drop calculations so that flow can be increased to the correct amount. In addition, the correction can be changed in a fairly predictable manner since the pressure drop is proportional to the land length. In the case of the shape-change approach, one of the problems is that the pressure is a cubic function of the channel depth making the adjustment very sensitive to the size of the effective channel. In operation the land length corrected die will generally have a significantly wider operating output range.

2. EFFECT OF THE DOWNSTREAM EQUIPMENT

The output capacity of an extruder does not necessarily determine the possible hourly production, since the extruder is only part of the extrusion system. The other frequently more important phase is the ability to-take off and cool at the desired production rate, while holding the spcified shape and tolerances. The appearance of the product is also dependent upon cooling rate and take-off speed. It is obvious that for short-run production, the cost of specialized cooling and take-off equipment must be limited, and stay in relationship to the quantity of the product to be produced. On the other hand, for long-run production, it has been proved that highly engineered and mechanized cooling and take-off machinery pays for itself rapidly, even though the cost of such take-off equipment might be considerably higher than that of the extruder and its drive. Such installations permit taking full advantage of high extruder-output rates.

It must be kept in mind that most of the drive-motor energy supplied to the extruder is used to heat up and melt the plastic to be extruded. In order to bring the melt back to the solid state, a large fraction of this heat must be removed from the extrudate within a short distance from the die. Shape and appearance of the hot molten extrudate have to be precisely maintained until sufficient cooling and setting have taken place. Therefore, when extruding a given product, cooling facilities have to be increased more than proportionately to increased extruder horsepower. Output increase for a given shape results in higher lineal take-off speed. This reduces the available "near-the-die" cooling time which is essential for proper shape holding.

The lineal take-off and/or cooling speed for a given cross section is often the principal limiting factor of extrusion production.

Cooling rates are different for various polymers. They are a function of the thermal characteristics of the respective material.

The cooling rate for a polymer does not increase or decrease linearly with wall thickness. This means that a section twice as thick as another requires more than twice the cooling time.

It can therefore be concluded that:

1) Dimensionally identical cross sections of differnet polymers will have different take-off speeds and production rates.

2) Thinner extrudates can be more easily cooled and permit higher lineal speeds. Thicker sections require disproportionately slower lineal speeds.

3) Take-off rates, i.e., pounds per hours, are determined by wall thickness and total surface area exposed to cooling.

Since wall thickness is a specified dimension, our ingenuity has to concentrate on the most efficient cooling devices. The simplest and most efficient way to cool is by good contact with a cooling liquid, or spray. In the case of pipe extrusion, the cooling rate is greatly increased by cooling internally as well as externally. This is done with a cooled mandrel. In the case of thin-film production, roll casting permits more efficient cooling than the blown-film process, because the film is in intimate contact with the cooled casting rolls on both surfaces.

Some polymers and some cross sections cannot be liquid-cooled. In these cases, elaborate shape-holding devices have to be used.

Multiple-die extrusion heads are frequently used to reduce lineal take-off speed and to permit the use of high extruder output. This technique is used in the production of blown film, pipe, and others. This method has proved its practical interest only in long-run installations, since the start-up is more complicated, and each die orifice generally requires its own take-off and cooling mechanism.

Monofilament production, multiple-strand wire covering, and compounding with multiple-strand heads are typical examples where "multiple die" operation has become the accepted method. Depending on the application, the economics of a large multiple-head extruder, compared to several smaller extruders and take-off trains, must be carefully evaluated.

A few examples of efficient cooling systems are:

a) internal-external bubble cooling during film extrusion as shown on Table 8 including figures A & B.

b) internal cooling of corrugated pipes - Table 9.

c) sizing dies for high speed profile extrusions as shown on fig. 19.

TABLE 8 FILM EXTRUSION COOLING SYSTEM

COMBINED EXTERNAL AND INTERNAL COOLING

A combined external/internal cooling system permits faster air velocities than those shown in Figure A—up to 100 to 130 ft/second (30 to 40 meters/second)—without causing bubble instability. This technique, now gaining popularity in Europe, nearly doubles the cooling efficiency. Other advantages of the system include the capability of maintaining cooling intensity independent of blowup ratio, closer gage and width tolerances, and the capability of cleaning the interior surfaces of the film of polymer fume deposits produced at the die exit, which reduces blocking tendencies.

In addition to permitting greater throughputs, a combined cooling system can reduce tower-height requirements and, consequently, building costs. However, film run at high output can exhibit reduced impact strength due to greater machine-direction orientation, which can also seriously affect heat sealability. For this reason, some companies do not opt for maximum production in terms of coolable output but base production figures on coolable film that is acceptable in both impact strength and sealability.

From a quality standpoint, it has been clearly demonstrated that both gage and layflat width can be more closely controlled with a combined internal/external cooling system. Gloucester calculates that gage control on its lines maintains tolerances at least as close as ±10 percent and that width tolerance is within ±0.118 inch (3 mm), almost completely independent of bubble size. A combined cooling system also permits the efficient use of the recently developed systems featuring integrated control, such as the IDC by Reifenhauser and the NC-E by Windmoeller & Hoelscher.

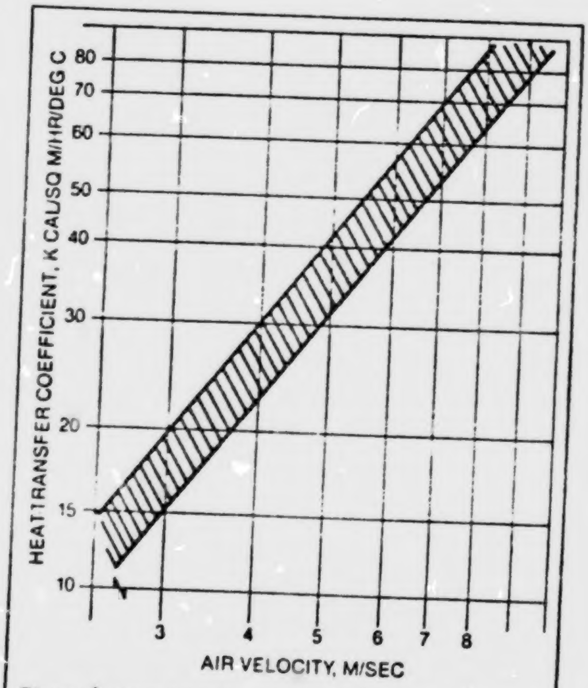


Figure A. Heat-transfer coefficients are shown as a function of air velocity.

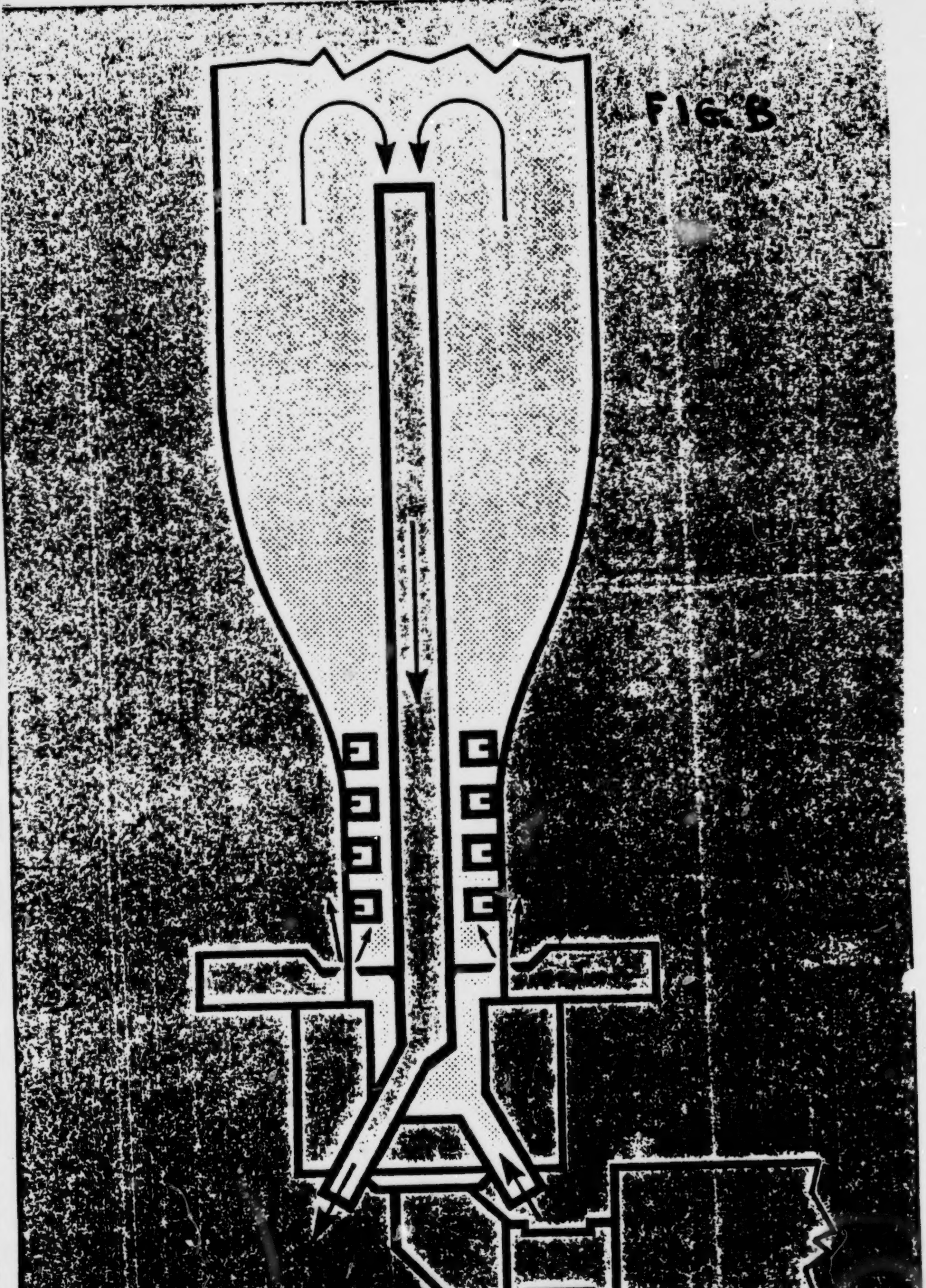
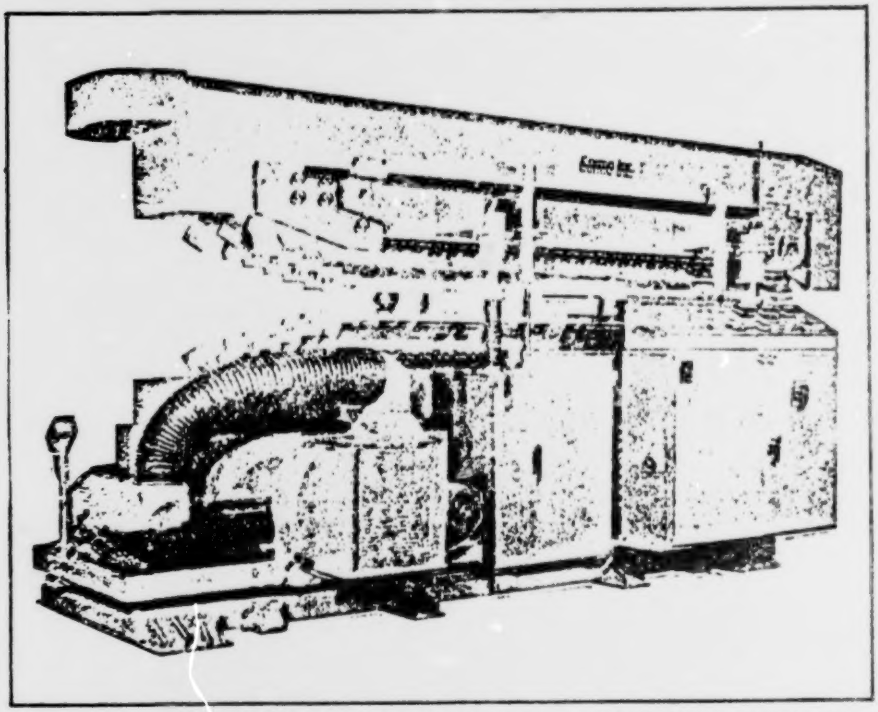


FIG. B

TABLE 9 CORRUGATED PIPE - COOLING SYSTEM



Model 1220 corrugator showing upper housing electrically lifted to the part-open position

Internal cooling

One of the most effective ways to cool a pipe is by internal cooling (*Fig.* B). Corma holds worldwide patents on internal pipe-cooling equipment.

Internal cooling permits increases in production speeds by up to 50%. Cooling the pipe from the inside as well as the outside also reduces stresses within the plastic.

With conventional corrugators, cooling of the pipe is achieved when the plastic comes in contact with the moldblock. This has the following disadvantages:

a) The chilled moldblock surface can freeze the outer skin of the pipe, thus spoiling the pipe finish.

b) The heat from inside the pipe will reheat and soften the pipe after it exits the corrugator. This makes it difficult to maintain the pipe profile and also can cause reduced production speeds when perforating pipe for drainage.

Product after-coolers

Product after-coolers are most important for pipe and tubing produced from the polyolefins, since these materials set up relatively slowly.

Corma offers three types of product after-cooler, as follows:

1) The *recirculating after-cooler*, which comes complete with a haul-off geared to the corrugator, a recirculating water pump and water blow-off station.

The haul-off keeps the pitch of the relatively-soft polyolefin pipe on specification while the profile is cooled and set in a flooded cooling pipe or water-spray shower.

2) The *spray atomizing cooling chamber*, which is used for the smaller pipe sizes or for slower-speed production.

3) The *air-chilled cooling chamber*, which has an automatic haul-off and incorporates its own air-chilling system. In this cooling chamber, there are approximately 16 m (50 ft) of pipe at any one time.

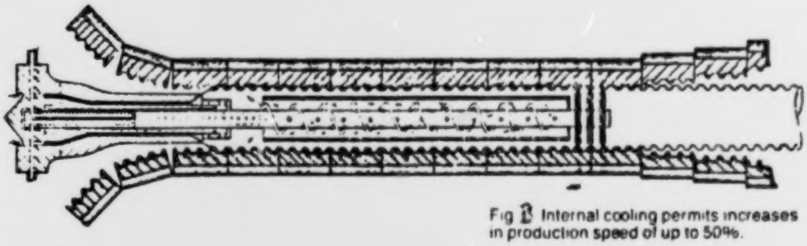


Fig 3 Internal cooling permits increases in production speed of up to 50%.

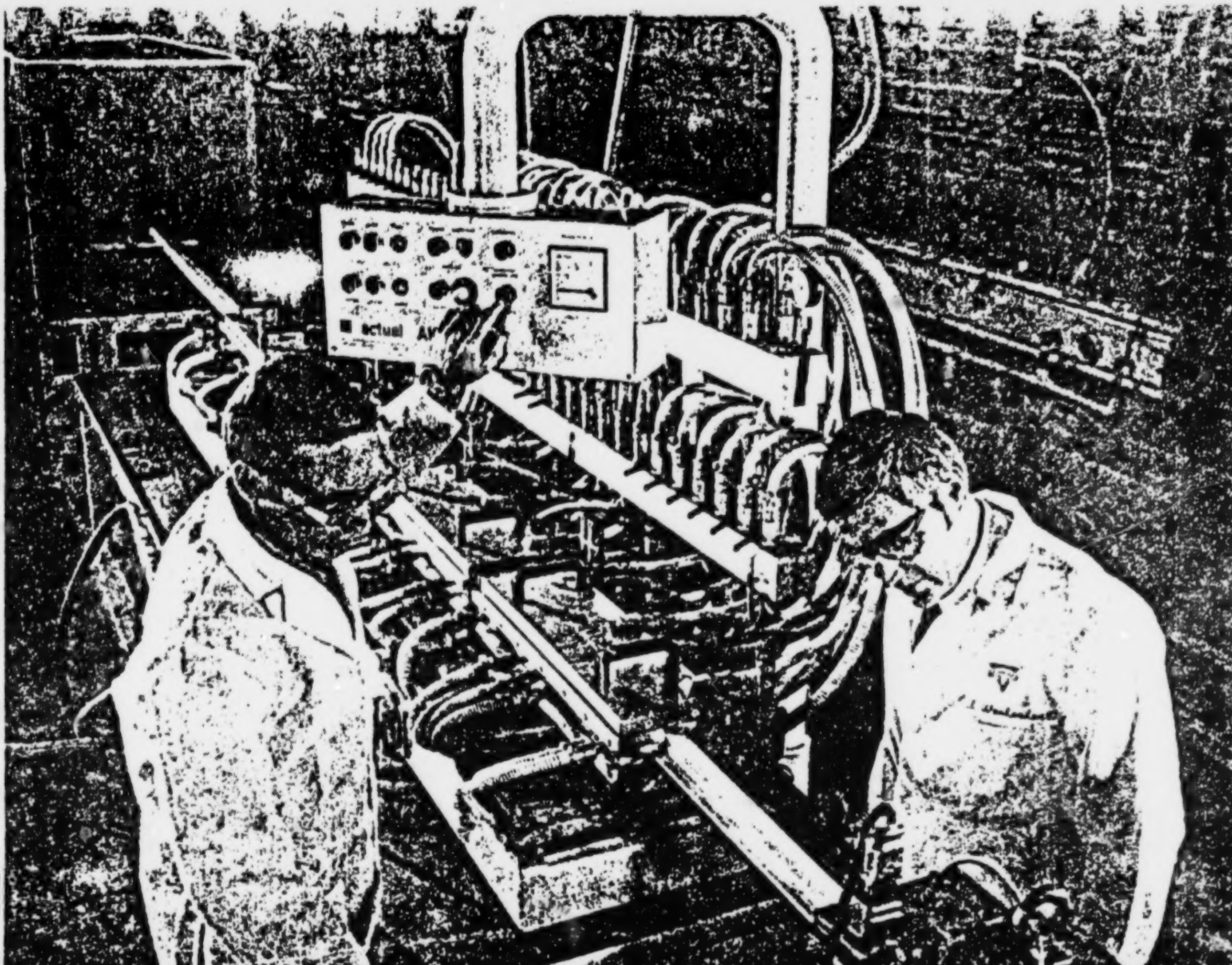


FIG. 19

We have just explained what effect the cooling rate has on the output and dimension quality, but of equal importance is its effect on internal strain in the extruded product. What gives the greatest influence on quality is internal strain. How to decrease internal strain given during the processing and how to eliminate the resultant internal strain are important. In other words, studies are necessary regarding the uniform cooling method and post treating techniques.

CRYSTALLIZATION

In extrusion of plastics, as the processing techniques and conditions are changed, molecular orientation, % crystallinity, crystal structures and the size of crystal are changed and so are the clarity, physical properties, dimensions and shape of the final product. Particularly in case of crystalline polymers, the factor which gives the greatest influence to the characteristics of the product is the degree of crystallinity. As an example, for polypropylene, the higher the tacticity, the higher will become the degree of crystallinity. Generally, as the molecular weight is greater, it is harder for the molecular chains to disperse. However, even if the molecular weight is the same, the degree of crystallinity will change depending on the processing conditions and heat history. Slow cooling raises the degree of crystallinity and quenching lowers the same. But quenching at even minus 40°C does not lower it below 60%. A material left at room temperature still shows gradual increase of the degree of crystallinity at the secondary crystallization, which adversely affects dimensional stability, decreases clarity, brings out bending, warpage and waving, and further causes degradation of physical properties.

INTERNAL STRAIN

In extrusion process, the internal strain is generally generated while cooling. One of the residual strains of this nature is caused by stretching and another is the cooling strain.

For the former, positive actions are taken to increase it, in order to improve physical properties of the product. Typical examples are melt spinning and stretched tapes (both are monoaxially stretched), biaxially stretched films, stretched pipes and blow-up films by inflation method.

The cooling strain is particularly noticeable in the manufacturing of relative thick wall products. For instance, the effects of the outside diameter sizing method and the inside diameter sizing method in pipe extrusion is a good example. The section first cooled after leaving the die is subject to compressive stress and the section cooled later is subject to tensile stress. Therefore, in case of the outsidde diameter sizing method, a pipe with tensile force working inwardly is made and what is contrasting to this, is a pipe made by the inside diameter sizing method. In case of the external cooling method, a remarkably high tensile stress is generated along the inner wall. For this reason, the inside diameter sizing method is more desirable for the resistance of pipe against internal pressure.

DOWNSTREAM EQUIPMENT AND AUXILIARY UNITS FOR EXTRUSION LINES

Some of the machines are limited to only one application, but most are multipurpose machines adaptable for several applications.

SHEET LINES

Sheet lines probably have units with the least degree of interchangeability with other product lines. The specific downstream units in the line are:

1. The three-roll cooling stack
2. Stripping roller units
3. Auxiliary blower cooling units
4. Gaging heads
5. Cut-off units-saws, shears, or hot wires
6. Sheet stackers

BLOWN FILM LINES

As previously mentioned, two different types of plastics film are made, and the lines required to make them involve some differences in the downstream equipment. The equipment required for blown film is:

1. Venturi ring support
2. Bubble cooling units
3. Cooling and blow-up tower
4. Pinch draw rollers
5. Bubble collapsing slats
6. Winder units
7. Film treater

ROD AND PROFILES

One of the differences between the tubing lines and the rod and profiles is that the shapes can be everything but round. Many of the units that are used with the tubed-and-pipe extrusion are used for the rod-and-profile lines. In some cases the units are modified to handle the odd shapes of the profiles. The line usually consists of the following equipment:

1. Fixturing rack to hold part shape
2. Vacuum sizer (optional)
3. Cooling unit - either air or water
4. Puller
5. Cut-off unit
6. Winder (optional)
7. Printer or marking unit (optional)
8. Embosser (optional)

Since the products involved in this category are diverse, the lines used in their manufacture will vary a great deal from each other.

PIPE AND TUBE LINES

The equipment requirements for downstream in the production of tubular products vary with the size of the product and with the material extruded. The equipment consists of:

1. Sizing unit
2. Cooling tanks
3. Auxiliary cooling units
4. Puller
5. Cut-off unit (optional)
6. Winder (optional)
7. Stacker or dump table (optional)
8. Marking unit

Two different methods for sizing tubular products are used when the product has the dimensions controlled by something besides the die opening and the pull rate. These are the internal-sizing cooling mandrel or an external vacuum sizing device. Some materials are extruded into tubing without any secondary sizing unit. This may be because the dimension and shape control resulting from free extrusion is adequate for the product requirement. The other reason is related to the properties of the material. Soft materials, such as flexible polyvinyl chloride compounds of urethane elastomers, are just about impossible to size mechanically because the hot polymer sticks to the sizer surfaces and prevents their movement through a sizer unit. Materials like this are free extruded into a water bath, and various types of fixtures are used to support the tubing and to maintain the shape as the material is cooled. The units are usually rings or rollers and, in some cases, are tubular, loosely fitting mandrels into which water is pumped to produce a high-velocity water flow on the surface of the tubing to improve the cooling rate. In general, the accuracy of the tube diameter and wall thickness is not as good with the free extrusion as it is with the controlled mandrel-type cooling and sizing devices.

There are also a number of optional units used on tubing lines:

1. Dry vacuum sizers
2. In-line marking units
3. Internal mandrel sizing units
4. Diameter-gaging equipment
5. Wall-thickness gaging equipment
6. Acoustical flaw detectors
7. Other special equipment

3. IMPORTANT THERMOPLASTIC PROPERTIES

We will now discuss the important material properties in extrusion, particularly how they affect the extrusion process.

a) Bulk properties

Important bulk material properties with respect to solids conveying are:

- bulk density
- compressibility
- particle size
- angle of slide/coefficient of friction
- moisture content

A high compressibility indicates a tendency of the material to pack. A compressibility of 20% or more means a high probability of bridging in the feed hopper. The hand squeeze test can give a qualitative measure of the compressibility. A highly compressible material will form a hard clump. A large angle of slide means that the material is likely to bridge or to cause solids conveying problems in the extruder; the same with a high coefficient of friction. Hygroscopic material will pick up moisture with time. As their moisture level increases they may become tacky and harder to convey, hence proper drying is necessary (See Fig. 20 to 23).

A rough classification of material can be made based on particle size, shape, compressibility, and slide angle. Such a grouping can quickly show potential problems in solids conveying.

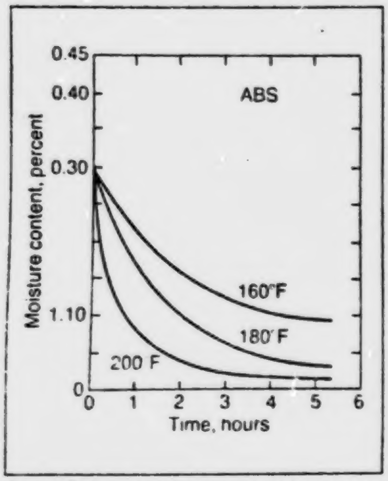


Figure 20 Temperature is probably the most important factor in drying plastic resins. Moisture content of ABS is shown after the material's exposure to air at different temperatures. Higher drying temperature had a marked effect.

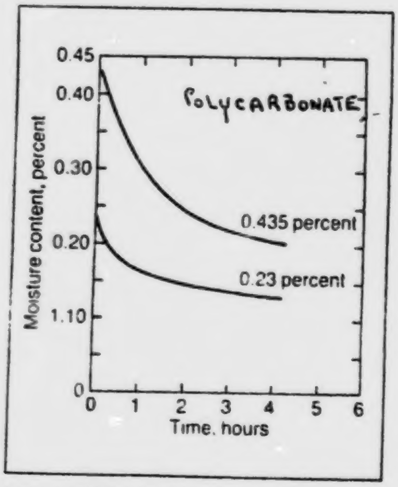


Figure 21 Effect of proper air flow is shown for polycarbonate. Most resin producers agree that the volume of air required to dry resins is about 1 cubic foot per minute for each pound of material passing through the dryer per hour.

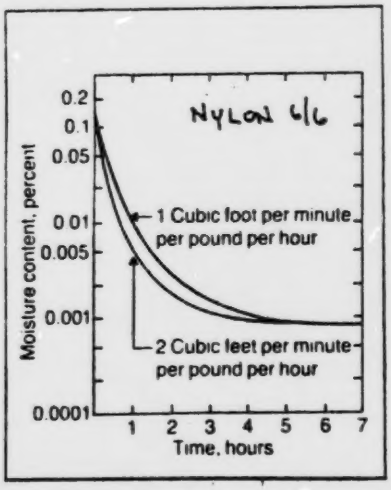


Figure 22 Initial and final moisture content have an important effect on drying time. Time required to dry Nylon 6'6 with two different initial moisture contents are shown. Eventually the two curves will reach the same equilibrium point.

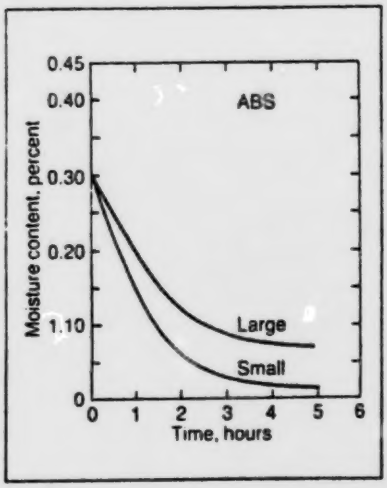


Figure 23 Configuration and size play important roles in plastics drying. Large and small pellets dry at different rates, as shown for ABS resin. The same principle applies when comparing drying rates of thin film and thick plastic sheets.

	Group I	Group II	Group III	Group IV
particle size	over 6 mil	6-2 mil	less than 2 mill	1/8"-1"
compressibility	less than 10%	10-25%	over 25%	Variable
slide angle	less than 30%	35-55°	over 35°	over 45°
bridging tendency	low	medium	high	high
type material	pellets	powder	fine powder	film scrap fiber scrap etc.
mesh size	< 100 mesh	100-300	> 300	

It must be noted that the bulk density changes again once the material is conveyed at the feed section of the screw as shown on fig 24.

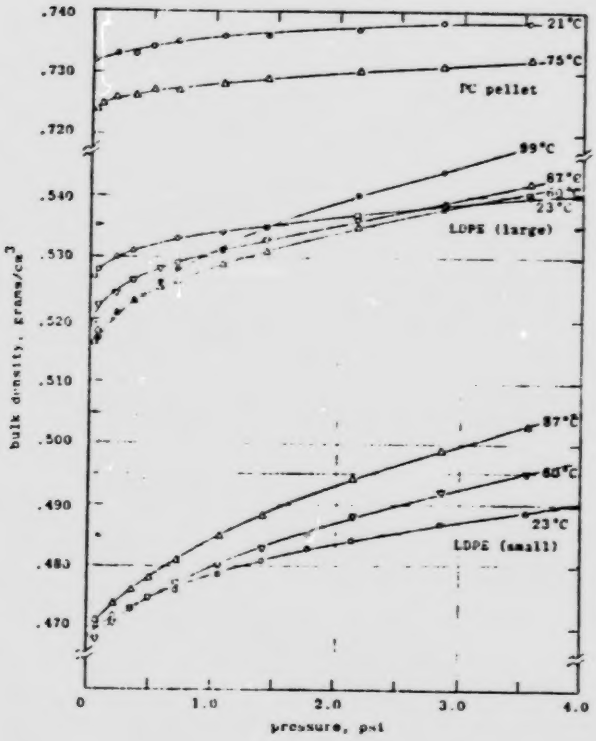
b) Thermal properties

Thermal properties are extremely important in plasticating extrusion since various thermal processes occur in the extruder: heating, conduction, melting, and usually cooling. The thermal properties of a polymer determine to a large extent the type of process that has to be used for the polymer.

One of the most important thermal properties is the thermal conductivity. It is a measure of the capability of a material to conduct heat. Polymers generally have very low thermal conductivities. They are thermal insulators and conduct heat poorly. Therefore, it is inadvisable to depend totally on conductive heating. In extrusion most heating is done by viscous heat generation for this very reason.

FIGURE 24

Effect of pellet geometry, temperature and pressure on the bulk density of resins in the solid conveying section of the extruder screw.



Another important property is specific heat. It is a measure of how much energy is required to raise the polymer temperature. The higher the specific heat the more energy will be required to raise the polymer to the temperature of the melt at the end of the extruder. If temperature rise an specific heat are known then a reasonable estimate can be made of the energy required for extrusion.

In semi-crystalline polymers another thermal property of importance is the latent heat of fusion. This is the energy required to melt the material. In many polymers, this heat of fusion is considerable; it ranges from 50 to 100 BTU/lb. Therefore, semi-crystalline polymers generally require a greater heat input to reach the desired processing temperature.

The melt temperature is a thermal property of obvious importance. The process temperatures must be over the melt temperature to ensure plastication and good melt flow behavior. Extruders are usually operated about 25 to 50°C over the polymer melt temperature. A high polymer melt temperature requires a high energy input. Longer extruders may be required for high melt temperature polymers. Another approach is to modify the screw design to enhance the melting performance.

Another important property is the induction time of the polymer as a function of temperature. It is the time elapsed at a certain temperature before the effects of degradation can be detected. The induction time of a polymer can be improved by adding stabilizers to the polymer. The induction time is an important parameter in polymer processing. If the process temperatures are known then the maximum allowable residence time can be determined. Vice versa, if the residence time is known the maximum allowable process temperatures can be established. Thus, the induction time is a very useful property both for the polymer chemist and the polymer process engineer.

Some of the main thermal properties of several important polymers are shown in tables 10-12.

TABLE 10 IMPORTANT THERMAL PROPERTIES OF SEVERAL POLYMERS

	DENSITY (GR/CC)	MELT TEMPERATURE (^{o}C)	THERMAL CONDUCTIVITY (10^{-4} cal/sec/cm/^{o}C)	SPECIFIC HEAT (CAL/^{o}C/GR)	HEAT OF FUSION (CAL/GR)
-Low Density Polyethylene LDPE	0.910-0.925	110-130	8.0	0.55	65
-High Density Polyethylene HDPE	0.941-0.965	120-140	11.0-12.4	0.55	70
-Polypropylene PP	0.902-0.910	176	2.8	0.46	15-60
-Polyvinyl Chloride PVC	1.30-1.58	>146	3.5-5.0	0.25-0.35	-
-Polystyrene PS	1.04-1.09	-	2.4-3.3	0.32	-
-Polycarbonate PC	1.20	-	4.6	0.28-0.30	-
-Polyamide PA-6	1.12-1.14	225	5.8	0.40	37-49
-Polybutylene terephthalate PBT	1.31-1.38	232-267	4.2-6.9	0.28-0.55	?

TABLE 11 THERMAL CONDUCTIVITIES OF SELECTED MATERIALS

Material	Thermal Conductivity (BTU/hr-ft-°F/ft)
Copper	226
Berylium Copper	110
Aluminum	92.5
Carbon Steel	27
Stainless Steel	14.5
Polyvinyl Alcohol	0.46
Melamines	0.41
Polyethylenes	0.19
Acrylics	0.15
Nylons	0.14
Styrene Butadiene & Nitrile Rubber	0.14
TFE Fluorocarbons	0.14
Acetal	0.13
Cellulose Nitrate	0.13
ABS resins	0.12
Nylon, glass filled	0.12
Polyester (cast)	0.12
Silicone rubber	0.12
Polycarbonate	0.11
PVC	0.10
Polypropylene	0.08
Polystyrenes	0.08
Preformed Polystyrene, rigid foam	0.018

TABLE 12 TOTAL ENTHALPY OF COMMON THERMOPLASTICS RESINS AT PROCESSING TEMPERATURES

Material	Approximate Total Heat at Processing Temp.			
	(Btu/lb)	(Btu/in^3)	(cal/g)	(cal/cm^3)
ABS	140-170	5.3-6.4	75-95	80-100
Acetal	180	11.1	100	145
Acrylic	125	5.4	70	80
Cellulose Acetate	125	5.8	70	90
Cellulose Acetate - Butyrate	120	5.2	65	80
Nylon	275-325	11.1-13.1	155-180	170-200
LDPE	250-300	8.3-10.0	140-165	130-155
HDPE	300-350	10.4-12.1	165-195	160-185
Polypropylene	250	8.2	140	125
Polystyrene, GP	120	4.6	65	70
PVC	70-150	3.6-7.8	40-85	55-115
SAN	120-150	4.7-5.9	65-85	70-90

c) Melt flow properties

Practically all polymers are shaped in the molten state. Therefore, the flow properties of polymer melts are important in most polymer processing operations. In extrusion the melt flow properties start to play a role from the point where the first traces of melt appear up to the point where the polymer leaves the die (see previous chapter on dies under extrusion equipment). The basic definitions of the main melt flow characteristics are shown on Table 13.

The viscosity is probably the most important melt flow property. It is a measure of the resistance that the fluid offers against flow. Thus it takes more energy to induce flow in a high viscosity fluid than in a low viscosity fluid. To achieve motion in a fluid requires exertion of a force on the fluid. If a shearing motion occurs in the fluid then a shear force is responsible for this motion. This force will work over a certain area of the fluid. The shear force divided by the area over which it works will give the shear stress. Thus, the shear stress causes a certain shear deformation in the fluid.

When shear deformation takes place, different fluid elements will have different velocities. Shear rate is a measure of the velocity difference between two fluid elements separated by a certain normal distance. The shear rate, therefore, is a velocity gradient. The higher the flow rate thru a certain cross section, the higher the velocity gradients will be and consequently the higher the shear rates will be. The proper definition now of viscosity is:

$$\text{viscosity} = \frac{\text{shear stress}}{\text{shear rate}}$$

TABLE 13

DEFINITIONS IN POLYMER FLOW

DRAG FLOW -	FLOW CAUSED BY RELATIVE MOTION OF BOUNDARIES (COUETTE)
PRESSURE FLOW -	FLOW CAUSED BY PRESSURE GRADIENTS IN THE FLUID
SHEAR -	OCCURENCE OF VELOCITY DIFFERENCES IN NORMAL DIRECTION
ELONGATION -	OCCURENCE OF VELOCITY DIFFERENCES ALONG A STREAMLINE
PLUG FLOW -	FLOW WITHOUT SHEAR
SHEAR RATE -	VELOCITY DIFFERENCE PER UNIT NORMAL DISTANCE (VELOCITY GRADIENT)
SHEAR STRAIN -	DISPLACEMENT PER UNIT NORMAL DISTANCE OVER CERTAIN TIME PERIOD
SHEAR STRESS -	STRESS REQUIRED TO SUSTAIN SHEAR FLOW
VISCOSITY -	RESISTANCE TO FLOW (SHEAR STRESS/SHEAR RATE)
NEWTONIAN FLUID -	VISCOSITY INDEPENDENT OF SHEAR RATE
NON-NEWTONIAN FLUID-	DILATANTS - VISCOSITY INCREASES WITH SHEAR RATE PSEUDOPLASTICS - VISCOSITY DECREASES WITH SHEAR RATE

For Newtonian fluids the viscosity is independent of the shear rate. Thus a plot of shear stress versus shear rate will be a straight line. Generally, a plot of shear stress versus shear rate is called a flow curve. The simple relationship between force and deformation in Newtonian fluids makes it relatively easy to describe the flow behavior of Newtonian fluids.

Unfortunately, polymer melts do not behave as Newtonian fluids. The viscosity of polymer melts reduces with increasing shear rate. In other words they flow more easily at high flow rates than at low flow rates. This flow characteristic is called "pseudoplastic behavior"; it is also referred to as "shear thinning behavior".

The two main types of fluid flow are laminar and tubulent flow. The transition from laminar to turbulent flow occurs at Reynold numbers of about 2000. the Reynold number is a dimensionless number that represents the ratio of inertia forces to viscous forces. The viscosity of polymers is very high (about 100,000 to 10,000,000 times higher than the viscosity of water) and the Reynold number associated with polymer melt flow very small. Therefore, polymer melt flow is always laminar flow (see Table 14).

Table 14 Viscosity of Selected Materials

Material	Viscosity, Pa . s	Viscosity, centipoises
Water	0.001	1
Kerosene	0.01	10
Motor oil	0.01 - 1	10 - 100
Glycerine	1	1000
Corn syrup	10	10 000
Molasses	100	100 00
Resins	< 0.1 to $> 10^3$	< 100 to $> 10^6$
Plastics (hot, viscoelastic state)	$< 10^2$ to $> 10^7$	$< 10^5$ to $> 10^{10}$

Thus in extrusion of polymers we deal with laminar flow of pseudoplastic fluids. To dertermine the extent of non-Newtonian behavior we have to determine the viscosity over a wide range of shear rates. This can be done on a rheometer. Three important types of rheometers are the capillary, the cone and plate, and the coaxial cylinder rheometer. The relationship between shear stress and shear rate for many polymers can be approximated with a power law equation. We speak of "power law fluids". The power law index is a measure of the degree of non-Newtonian behavior; it equals one for a Newtonian fluid and approaches zero for very strongly non-Newtonian fluids.

For most polymers the power law index ranges from 0.9 to 0.2. It is important to know the power law index, since it strongly affects the flow behavior of a polymer. Thus, we have seen that the polymer viscosity is dependent on the shear rate. Another factor that affects the viscosity is temperature. The temperature effect on viscosity can also be measured on a rheometer. In general the viscosity decreases with increasing temperature.

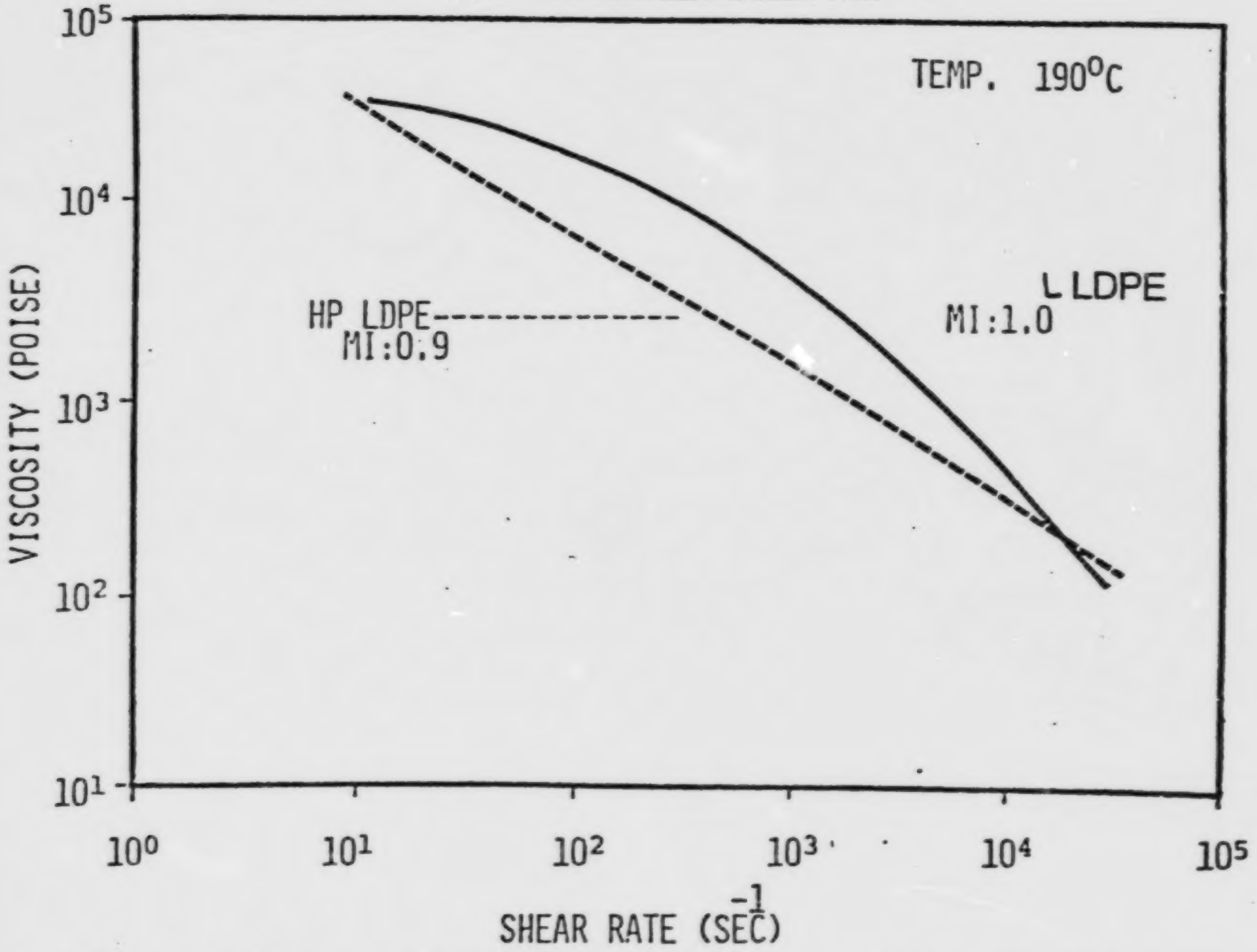
One important facet of viscous flow is the viscous heat generation in the fluid. This can be thought of as occurring because of the internal friction within the fluid. It is a major source of heat in extrusion. Therefore, it is important to understand the role of viscous heat generation. For a Newtonian fluid and pure shear it is:

$$\text{viscous heat generation} = (\text{viscosity}) \text{ x } (\text{shear rate})^2$$

Thus at high viscosities and shear rates we can expect a large amount of viscous heat generation (see Figs. 25,26).

Molecular weight distribution for a given polymer is known to have a significant effect on processing behavior and this is largely because of its effect on shear sensitivity. In general, the narrower the distribution range, the lower will be the shear sensitivity or the

FIG. 25



EFFECTS ON CONVENTIONAL HP-LDPE EXTRUDERS

- HIGHER MELT TEMPERATURES
- MORE POWER REQUIRED
- HIGHER BACK PRESSURES
- TENDENCY TO MELT FRACTURE

flatter the viscosity vs shear rate curve and the higher the apparent viscosity at high shear rates for any given level of melt index or other low shear flow test value. The molecular weight distribution can be varied in many ways, both in the polymerization processes and by after blending of materials having different MWD ranges. Unfortunately, it cannot always be predicted and controlled as well as one might desire and some lot-to-lot variations will exist. Also, presumably equivalent products made by different suppliers by the same or different processes will not necessarily have the same viscosity characteristics or processing behavior. Accurate viscosity-shear rate measurements will uncover such differences, however, and usually explain observed behavioral effects.

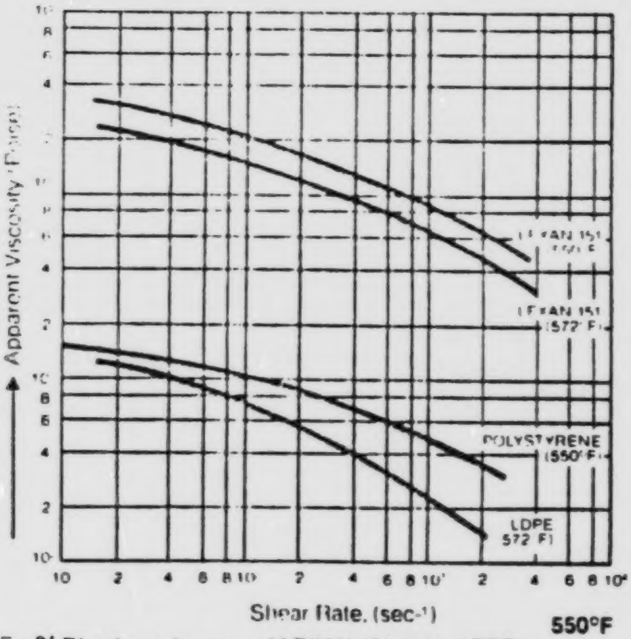


Fig 2b Rheological curves of LEXAN 151 resin. LDPE and POLYSTYRENE

d) Other Properties

We have discussed the most important polymer properties with respect to extrusion. However, there are many other properties that have to be considered to make sure that the extruder can run smoothly over a long period of time. It is impossible to mention here all the polymer properties of importance. Each particular situation should be carefully studied to determine what properties play a significant role.

For instance, whether or not a particular material melts sharply at a single temperature or throughout a broad range of temperature is of some importance. In general, cystallline polymer melt sharply or over a narrow range whereas amorphous polymer or those with a low degree of crystallinity soften or melt over a broad range. The sharpness of the melting point is important in processing since it affects the time required for complete transition from solid pellets into a fluid melt. This, in turn, affects both the volumetric efficiency of the screw and screw design for any given job.

Additives in a compound also greatly influence the resin behaviour in an extruder as shown on the following tables 15 and 16.

TABLE 15 Additives that Assist

Processing	Modify Mechanical Properties	Reduce costs	Modify surface properties
Blowing agents	Impact modifiers	fillers	Antistatic agents
Heat stabilizers in PVC	(MBS, ABS, CPE, EVA, others)	$CaCo_3$ Talc	slip & antiblock
		Kaolin	additives
lubricants	plasticizers	Mica (a)	
colorants	reinforcers (glass fiber, carbon, etc) (a)		
coupling agents (titanate - lower viscosity)			
acrylic processing acids			

Table 16 Thermal properties of some thermoplastics and some fillers

Material	Thermal conductivity (W/(m x K))	Specific heat (kJ/(kg x K))
LDPE	0.32 to 0.40	2.1 to 2.5
HDPE	0.38 to 0.51	2.1 to 2.7
PP	0.17 to 0.23	1.6 to 2.0
PS, ABS	0.18	1.3
rigid PVC	0.14 to 0.17	0.85 to 0.90
PA	0.23 to 0.29	1.6 to 2.0
PC	0.21	1.2
calcium carbonate	2.4 to 3.0	0.86
talcum	2.1	0.86
kaolin	1.9	0.92
mica	2.5	0.86
PP	0.23	1.68
PP + 20% $CaCO_3$	0.42	1.47
PP + 40% $CaCO_3$	0.56	1.34

Table 16 reveals that mineral fillers have thermal conductivities which are up to 20 times higher than those of the plastics. Moreover, their specific heats only exhibit half the value compared with the plastics. Thus in heating or cooling a filled plastic less energy is spent or removed respectively as compared with the unfilled sample. Besides, owing to the higher thermal conductivity, the cooling process proceeds considerably more rapidly.

Another point worthwhile mentioning is the interaction between the polymer and the surface of screw and barrel. If the polymers-or rather the additives with the polymer - are abrasive, special precautions have to be taken to prevent premature failure of the extruder. For instance, in extrusion of glass fiber reinforced polymer wear resistant surface coatings must be used to minimize the effect of wear. Similar problems occur when the polymer attacks the screw and barrel by corrosion (fluoropolymers). In this case corrosion resistant materials of construction have to be applied. Anticipating such problems can prevent lengthy extruder down-time.

4. OPERATIONAL PRINCIPLES OF EXTRUDERS

The three most common and most important functions of an extruder are solids conveying, plasticating and melt conveying as shown in figure 27. The different functions are governed by different mechanisms of conveying, heat and mass transfer, and mixture. It has been pointed out that the location of these three zones does not coincide with geometrical sections of the screw such as the feed, transition and metering but instead depends on the operating conditions. The three main functions of the extruder will now be described in more detail.

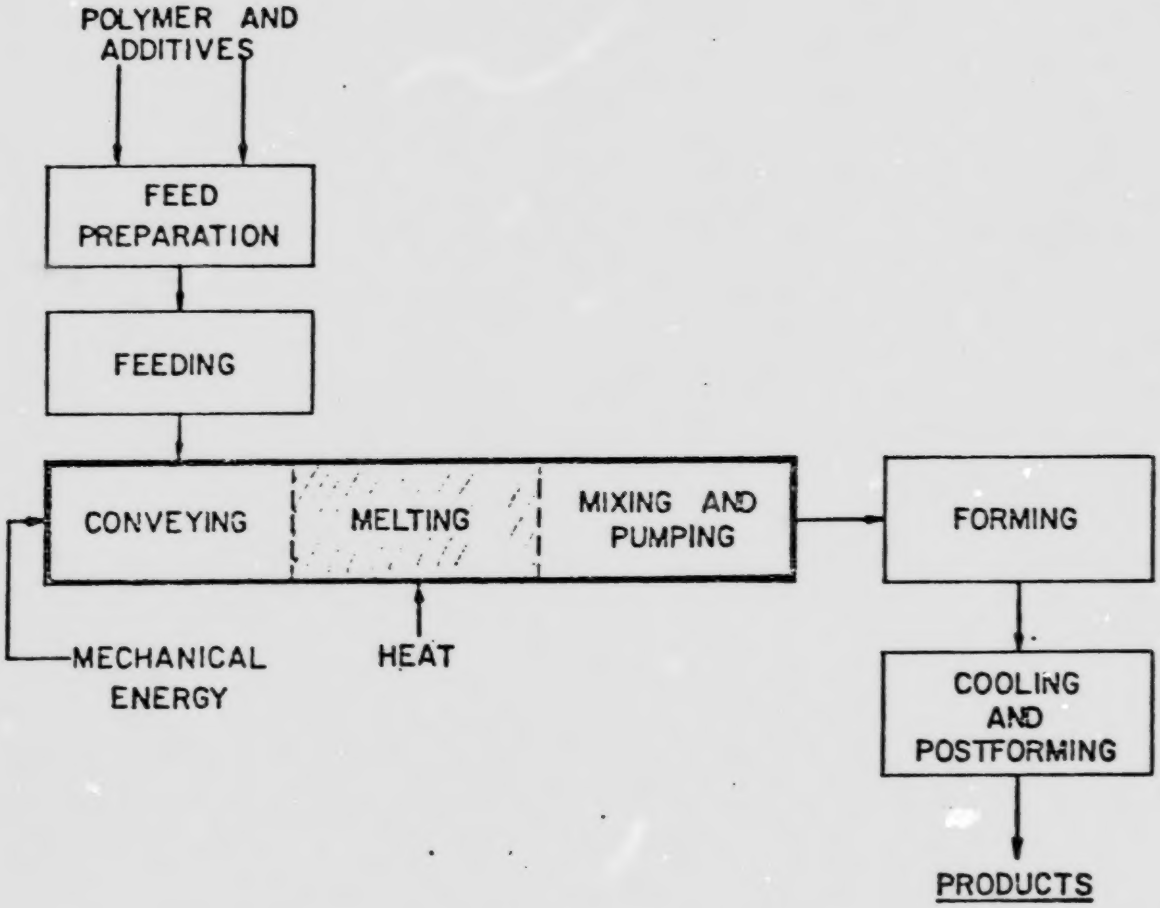
a) Solids Conveying (1st operation in the process)

The polymer is usually fed to the extruder from a hopper. It flows from the feed hopper through the feed port opening into the extruder barrel. The flow takes place by the gravitational forces acting on the polymer, therefore the term gravity feed. The rate is controlled by the intake capacity of the extruder screw. This situation is called "flood feeding". In some cases, the amount of material fed to the extruder is intentionally limited. This is called "starve feeding". In this case, the material is usually metered into the extruder feed opening by means of a conveying device (belt feeder, auger feeder, etc.).

In some cases, unintentional starve feeding occurs, causing variations in extruder performance. These problems are associated with flow instabilities in the feed hopper (low level, poor design, bridging, etc.) or in the feed throat (poor feed port design, polymer sticking to the screw, etc.). The geometry of the hopper and the characteristics of the feed stock determine the flow behavior in the hopper.

Flow problems in the feed hopper can be solved in several ways. Vibrators can be attached to the hopper to prevent the build-up of static electricity. The discharge angle and discharge opening have to be designed to minimize the obstruction to flow. With very difficult to feed materials

FIGURE 27


POLYMER AND ADDITIVES
FEED PREPARATION
FEEDING
CONVEYING
MELTING
MIXING AND PUMPING
FORMING
MECHANICAL ENERGY
HEAT
COOLING AND POSTFORMING
PRODUCTS

forced feeding can be used. In this case, one no longer relies on the gravitational force to feed the material into the extruder barrel.

The conveying mechanism in the extruder is based on friction. The particulate polymeric material is compacted into a solid bed as it falls into the screw channel and is conveyed forward against increasing pressure. The main forces acting on the solid bed are frictional forces. These forces are responsible for the conveying action of the solid material. In order to understand the solids conveying in an extruder it is important to understand the friction characteristics of the material.

The frictional forces can be divided into two main groups. The frictional forces on the barrel and on the screw. The frictional forces on the barrel provide the positive conveying forces. The frictional forces onn the screw are the negative or retarding forces. This can be understood by comparing the solid bed to a nut on a bolt, where the bolt is the extruder screw. If the bolt rotates the nut will simply rotate with the bolt if the nut is not restricted in its rotation.

However, if we prevent the nut from rotating it will move forward axially relative to the bolt. Thus, if the solid bed had no friction against the barrel it would just rotate with the screw and not move forward. On the other hand if the friction against the barrel is large the solid bed will move forward at a high rate. Table 17 indicates the major variables affecting solid-conveying.

This conveying mechanism explains why a grooved barrel liner is beneficial for solids conveying. A grooved liner increases the frictional force on the barrel and with it the solids conveying capacity. By the same token we want to minimize the retarding forces. Thus, we want the screw surface to be as smooth as possible. Therefore, chrome plating is often used on the screw surface.

Table 17 Major Parameters Affecting Frictional Properties (Solid Conveying)

---

hopper design
height of the solid in the hopper (gravity feed)
force feeding (cramer feeder)
temperature of the resin in the hopper and inside the barrel
geometry of the resin particles (Bulk density)
coefficient of friction - resin or compound
temperature of the barrel (thermal conductivity)
screw design (channel depth, etc.)
type of metal surface of the barrel
feeding speed (screw RPM)

b) Plasticating

In the solids conveying zone the temperature of the material will gradually rise. This will occur because of the heat conducted into the material from the barrel heaters and also because of the frictional heat generated. The frictional heat is generated because of the relative velocity between the solid bed and the barrel and also the screw. This heat is directly proportional to the local pressure. Thus the higher the pressure the higher the temperature.

When the temperature of the solid bed approaches the melt point, plasticating or melting will occur. From this point on, the solids conveying mechanism no longer prevails, since solid to solid friction is no longer the only mechanism at work. A certain amount of melt will form and the conveying mechanism will have to include the effect of the viscous melt.

Obviously, the important characteristic of the melting zone is a continuous transition of solid material into molten material.

The length of the plasticating zone is determined by the thermal properties of the polymer, the operating conditions, and the screw geometry. Numerous melting theories have been proposed in the last twenty years. The aim of these theories is to quantitatively describe the above mentioned interactions. Unfortunately, the mathematical complexity of these theories is considerable. We will consider only the basic melting mechanism and its implications.

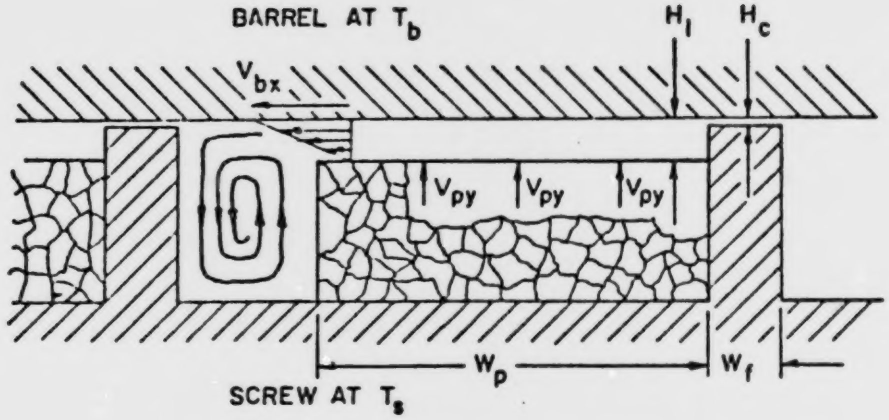
The basic melting model is shown in figure 28. It shows the solid bed surrounded by a melt film and a melt pool between the solid bed and the active screw flight. Two sources of heat are available for melting. The first source is the heat generated in the melt film because of the internal friction in the material, "viscous heat generation". The second source is the heat conducted into the material from the barrel heaters.

The viscous heat generation is primarily dependent on the viscosity of the fluid and the shear rates in the melt film. The shear rate equals the velocity gradient. High viscosity and high shear rates result in a high level of viscous heat generation. The advantage of viscous heat generation is that the heat is generated in the material where it is needed.

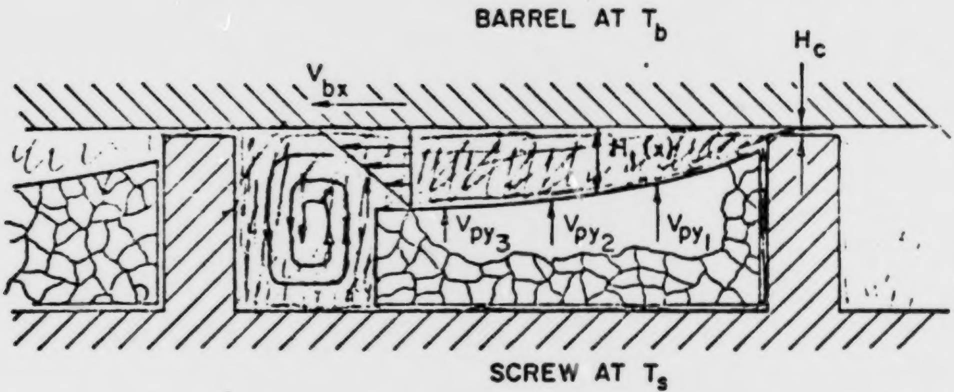
The heat conducted into the material from the barrel heaters has to travel over a considerable distance before it gets to the solid bed. Heat conduction thru the barrel is not a problem because of the high thermal conductivity of the barrel. However, heat conduction thru the melt film is more of a problem because most polymers have low thermal conductivities. Thus, to conduct a large amount of heat into the solid bed requires large temperature differences. This can be detrimental to the polymer, particularly in thermally unstable polymers.

In most extrusion operations the majority of the energy required for extrusion is supplied through the screw. This energy is transformed into heat by frictional and viscous heat generation. Only a small portion of the energy is supplied by the barrel heaters. Of course this will depend on the screw design, material properties, and operating conditions.

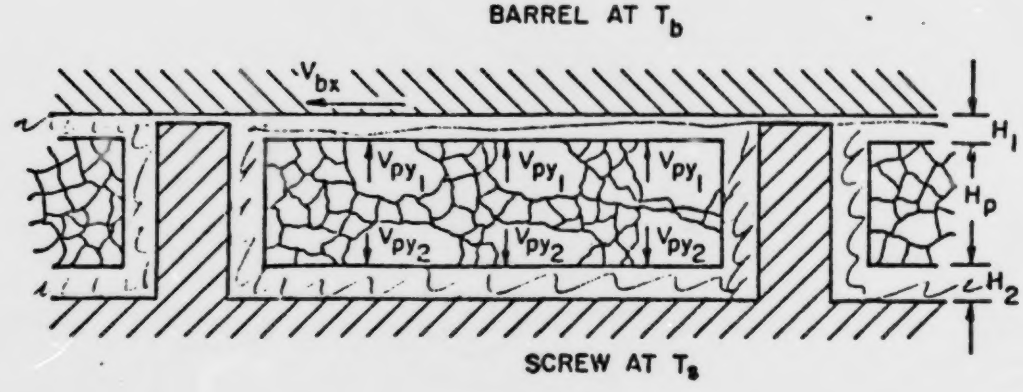
FIGURE 28


BARREL AT T_b
H_1
H_c
V_{bx}
V_{py}
V_{py}
V_{py}
W_p
W_f
SCREW AT T_s

IDEALIZED CROSS SECTION IN TADMOR MODEL


BARREL AT T_b
H_c
V_{bx}
$H_1(x)$
V_{py_3}
V_{py_2}
V_{py_1}
SCREW AT T_s

IDEALIZED CROSS SECTION IN MODIFIED TADMOR MODEL


BARREL AT T_b
V_{bx}
V_{py_1}
V_{py_1}
V_{py_1}
V_{py_2}
V_{py_2}
V_{py_2}
H_1
H_p
H_2
SCREW AT T_s

IDEALIZED CROSS SECTION IN LINDT MODEL

c) Melt Conveying

At the end of the melting zone or plasticating zone, all the solid material has molten. From this point on, we are in the melt conveying zone. There are two conveying mechanisms at play in the melt conveying zone. The first one is a viscous drag, caused by the viscous nature of the polymer. The material flow caused by this viscous drag is called the drag flow. The second conveying mechanism is pressure flow, caused by a pressure difference along the melt conveying zone. This flow is also called back flow, because it is usually in the negative direction. However, this is solely dependent on the pressure gradient. If the pressure gradient is posibive the pressure flow will flow back. If the pressure gradient is negative the pressure flow will flow forward. Negative pressure gradients can occur in normal extrusion situations. Therefore, the term back flow is not entirely correct.

It is convenient to be able to predict the extrusion rate as a function of screw speed and screw geometry. The total output of a screw metering pump in its simplest form is:

$$Q = QD - QP - QL \qquad (1)$$

QD = drag flow of the polymer conveyed downstream
QP = pressure flow resistance to polymer flow
QL = leakage flow due to a finite clearance between screw and barrel (3-5% loss of flow rate)

Within and accuracy of 10% equation (1) can be approximated by

$$Q \cong QD \qquad (2)$$

The drag flow is derived from

$$QD = \tfrac{1}{2}\ F\ n\ \pi\ DN\ h\ (t/n - e)\ \cos^2 \phi \quad (in^3/min) \qquad (3)$$

Making the assumptions that:

Drag flow shape factor equals 0.95
Single flighted square pitch screw
Flight width equals 10% of screw diameter

Equation 3 reduces to:

$$QD = 1.2127\ D^2\ Nh \quad (in^3/min) \qquad (4)$$

This volumetric flow rate can be converted to a mass flow rate by using the polymer melt density (p) in gm/cc and rearranging the units to give:

$$QD = 2.6275\ D^2\ Nhp \quad (lbs/hr.) \qquad (5)$$

Melt densities of various polymers at their normal processing temperatures and a operating pressure of 2,000 psi are listed below.

Equation 5 can easily be programmed into a hand held calculator to quickly obtain the screw drag flow rate. The program user can then change any of the screw parameters and receive a new answer in less than 10 seconds.

Polymer	**Melt Density GM/CC**
ABS	1.06
Acetal	1.16
Acrylic	1.03
Cellulosics (CA, CAB, CAP)	1.04
High Density Polyethylene	0.78
Low Density Polyethylene	0.76
Nylon (6,66)	0.98
PVC (Rigid)	1.27
Polycarbonate	1.18
Polyester (PET)	1.21
Polypropylene	0.72
Polystyrene	1.00

If the actual screw output varies by more than 10% of the drag rate then other process variables must be examined. The most common questions to be asked are:

- Is either the screw or barrel excessively worn?
- Is the screw metering depth mismatched for the polymer viscosity being processed?
- Is the polymer melt temperature excessively high?
- Is the screw speed excessively high?
- Is the die back pressure excessively high?
- Are there any burned out heater bands, blown fuses or malfunctioning temperature controllers?
- Is the screw L/D ratio short resulting in unmelted polymer - at the die?
- Are there mixing devices or barrier sections which are causing restrictions?
- Is the feedstock highly lubricated or does it have a low bulk density? If so, then better methods of solids conveying must be incorporated into the operation.

NOMENCLATURE

Q = total screw flow
Q_D = screw drag flow
Q_P = screw pressure flow
Q_L = screw-leakage flow
F = drag flow shape factor
n = number of parallel screw channels.

D = screw diameter (in)
N = screw speed (RPM)
h = screw channel depth (in)
t = screw lead (in)
e = screw axial flight width (in)
ϱ = polymer melt density (gm/cc)
ϕ = screw helix angle (°)

d) Venting and mixing

Venting is done on some extruders to extract volatiles from the polymer. These can be moisture, solvents, gases formed by a chemical reaction, etc. The volatives are generally extracted thru a vent port in the barrel. The vent port can be connected with a vacuum pump to improve the venting operation.

It is important that the screw design is carefully adapted to the venting operation. It is imperative that the pressure of the polymer at the vent port is zero. If not then the polymer will flow into the vent port and plug it very quickly. A single screw extruder is not an efficient machine for venting because of its low surface generation. If a considerable amount of venting is required multiple vent ports can be incorporated along the extruder barrel. However, this results in very long extruders.

Twin screw extruders are considerably more efficient in venting than single screw extruders.

As the material passes through the extruder a certain amount of mixing takes place. The mixing action can be improved by increasing the diehead pressure. One way of doing this is by placing screens in front of the breaker plate. The screw can be modified to improve mixing. This usually means the incorporation of a mixing section in the metering section. Numerous designs of mixing sections are available and there is little agreement as to which design is most efficient.

Mixing sections can have many different features, including pins, grooves, axial flights, reversed flights, interrupted flights, barriers, etc. They are all supposed to break up the prevailing flow pattern. This disruption of the flow pattern always results in extra viscous heat generation and in reduced conveying capacity. Therefore, the mixing should be limited to prevent excessive temperature rise and loss of output. As with venting, twin screw extruders are more effective mixers than single screw extruders.

C - TROUBLE SHOOTING EXTRUDERS

There are two important ingredients in trouble shooting. The first one is a good understanding of the extrusion process. The previous chapters should provide sufficient information to develop a good grasp of the basics of extrusion. The second ingredient is the requirement for good instrumentation (see extrusion equipment). An important requirement for trouble shooting is a logical step by step approach. For instance, change only one variable at a time, give the extruder a chance to stabilize after a change is made, etc.

We should distinguish two types of problems. The first one is a problem occurring in an existing extrusion situation. In this case the extruder ran well for a considerable period of time and then developed a problem. Our goal here is to establish the same situation as before the problem crept up. We will call these problems "upsets". These problems can always be solved! The other type of problem is one where we are trying to achieve an extrusion situation that has not been achieved before. We will call this a "development problem". This type of problem is not necessarily solvable. It may be an inherently insolvable problem.

MACHINE OR MATERIAL PROBLEM

We should determine if the problem is machine or material related. If a materials-quality control on incoming material is available, a check can be made if a drastic change in feed stock properties was determined. Another check is to take some old material that was used before the problem occurred and to extrude it. If we do determine the problem to be a material problem we can change back to the old material or readjust the extrusion conditions to compensate for the changes in material.

If the problem is not material related it must be machine related. There are four main categories of machine related problems. These are wear problems, melting problems, pumping problems, and solids conveying problems. We will discuss each category in more detail.

1 - Solids conveying problems

Solids conveying problems are difficult to pin down. Fluctuations associated with solids conveying often have a frequency equal to the screw speed. This can be reduced by using a multi-flighted screw design. Solids conveying problems often are combined with erratic drops in the drive motor amperage. Solids conveying problems can often be determined by a simple process of elimination. If the problem is not associated with the material, wear, melting, or pumping then most likely it is a solids conveying problem.

If a solids conveying has been established then the question is if the problems occurs in the feed hopper or in the extruder. A sight glass in the bottom of the hopper or better yet a transparent section in the pipe connecting the hopper to the extruder allows to determine if the material is flowing from the hopper to the extruder. Flow problems in the hopper can be solved with vibrating devices or static eliminators. If that does not work the hopper design may have to be changed. As a last resort, forced feeding can be used to ensure proper feeding.

If the solids conveying problem is associated with the extruder, several options are open. The first try should be made by adjusting the temperatures in the feed zone. If the relationship between coefficient of friction and temperature is known, the barrel temperature should be adjusted such that the friction on the barrel is maximum. If screw temperature adjustment is possible the temperature should be adjusted such that the friction on the screw is minimum. The surface of the screw should be smooth and the barrel surface should be rough. Therefore, grooved barrel liners have a beneficial effect on the solids conveying capacity.

If the screw design is optimized for solids conveying the following options can be incorporated:

- smooth low friction screw surface
- use large radius at the transition from flight to screw root
- double flighted design
- optimize helix angle and channel depth

Again forced feeding can be a last resort to solve the solids conveying problem.

2 - Melt conveying problems

These problems are associated with the pumping of the molten polymer in the metering section of the extruder. If the problem is insufficient thruput a quick check can be made to see how the actual pumping rate compares to the predicted pumping rate, using the equation (pages 78-81). If the predicted rate is considerably higher than the actual rate the problem is more likely to be a solids conveying or melting problem. If predicted and actual rate agree reasonably well, the design of the metering section will have to be improved. The main design parameters are the channel depth and the helix abgle. Using the previous equation, these parameters can be optimized quickly.

If the pumping is associated with excessive diehead pressure, the screens and the die should be checked. Ideally, pressure transducers are mounted before and after the screen pack. This way the pressure drop exceeds a certain value the screens can be changed. If the pressure drop across the screens cannot be measured, the screens have to be inspected visually to check for buildup of contamination. If the frequency of required screen changes is high automatic screens changers can be beneficial. In checking the die, the die heaters must be inspected. Low temperature of the polymer melt in the die can cause excessive diehead pressure. We should check if the cross sectional open area of the die is sufficient to allow the polymer to flow thru it. Improper die design can also create very high diehead pressures. If high diehead pressures cannot be avoided the channel depth of the metering section will have to be relatively shallow. This improves the pressure generating capability of the extruder.

Another problem can be excessively high temperature of the melt at the end of the extruder. This is generally caused by too much viscous heat generated in the extruder. In the simplest case the problem can be solved by adjusting the barrel temperature. However, in many cases temperature adjustment does not solve the problem. If the barrel temperature is reduced the viscosity at the barrel wall will increase and thus the viscous heat generation will increase. If the barrel temperature is increased the viscosity at the barrel wall will decrease and thus the viscous heat generation will decrease. However, in this case the temperature of the melt can rise because more heat is conducted into the polymer from the barrel heaters. Thus, an important factor is the temperature sensitivity of the polymer viscosity. If barrel temperature adjustment fails, starve feeding can be tried. This generally reduces the specific energy input and thus reduces the temperatrure rise in the material from frictional and viscous heat generation. The last resort then is a change in screw design. Increasing the channel depth reduces the shear rate and thus reduces the viscous heat generation. However, the channel depth cannot be increased too much because this can result in insufficient pressure generating capacity , as mentioned above.

3 - Melting problems

Insufficient plasticating capacity can cause extrusion problems. This problem is not always easy to detect. One method to determine if a melting problem exists, is to raise the barrel temperature in the transition section. If the results in an improvement of the problem, this is a good indication of a melting problem. If it aggravates the problem then a solids conveying problem is more likely to exist. Obviously, if unmolten polymer can be observed at the die this is a sure sign of a melting problem.

Fluctuations associated with melting problems usually have a frequency about five to ten times the frequency of screw rotation. This is thought to be caused by break-up of the solid bed. Break-up of the solid bed is likely to occur when the solid bed accelerates, It has been shown that no significant solid bed acceleration takes place in the absence of a melt film between the screw and the solid bed. This can be achieved by screw cooling. Unfortunately, this reduces the extrusion capacity.

Another method to check if a problem is related to melting, is to preheat the polymer. If this reduces or eliminates the problem, it is probably a melting problem. If preheating is an acceptable mode of operation, it can be a solution to the problem. Generally, it will be best to optimize the screw design with respect to melting capacity. This can be done by incorporating the following design options into the screw design:

- multiple flights
- increased pitch
- barrier flight
- increased taper.

4 - Wear problems

Wear problems can only be detected by disassembling the extruder and by inspection of the screw and barrel. We can differentiate between short term and long therm wear problems. Long term wear problems occur over a number of years and can be corrected by simple replacement of the worn parts.

Short term wear problems are generally more serious. They occur over a number of days or weeks. Continuous replacement of the worn parts would result in excessive downtime. In cases like this, a change must be made to the extruder to reduce the wear rate. In case of corrosive wear, corrosion resistant materials of construction can significantly reduce the problem. If the wear is of an abrasive type, wear resistant surface coatings can be used. Numerous coatings are available for extruder screws and extruder barrels (see screw construction, page 19).

Abrasive wear can also be reduced by optimizing the addition of the abrasive component. For instance, if glass fibers are added with solid polymer pellets, high wear rates occur. However, if the glass fibers are added at a point where the polymer is molten the wear rates are significantly lower. Sometimes high pressure gradients in the extruder can deflect the screw into the barrel. This can happen even on single screw extruders! The best remedy in this case is to change the process conditions or the design to eliminate the steep pressure gradients.

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PROGRAM
FOR
PROFESSIONAL DEVELOPMENT

INJECTION MOLDING
TECHNOLOGY

by

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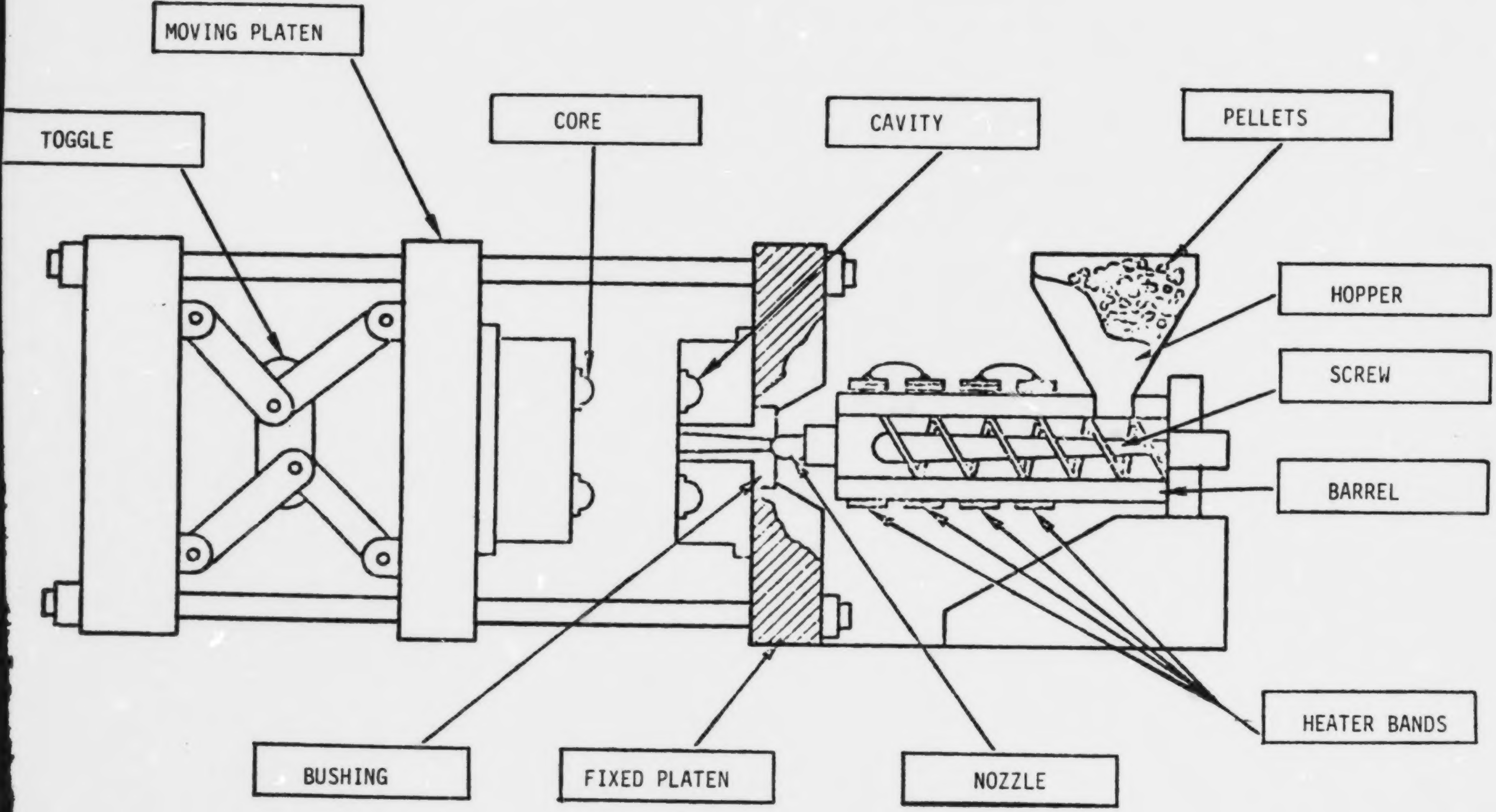
MOVING PLATEN
TOGGLE
CORE
CAVITY
PELLETS
HOPPER
SCREW
BARREL
HEATER BANDS
NOZZLE
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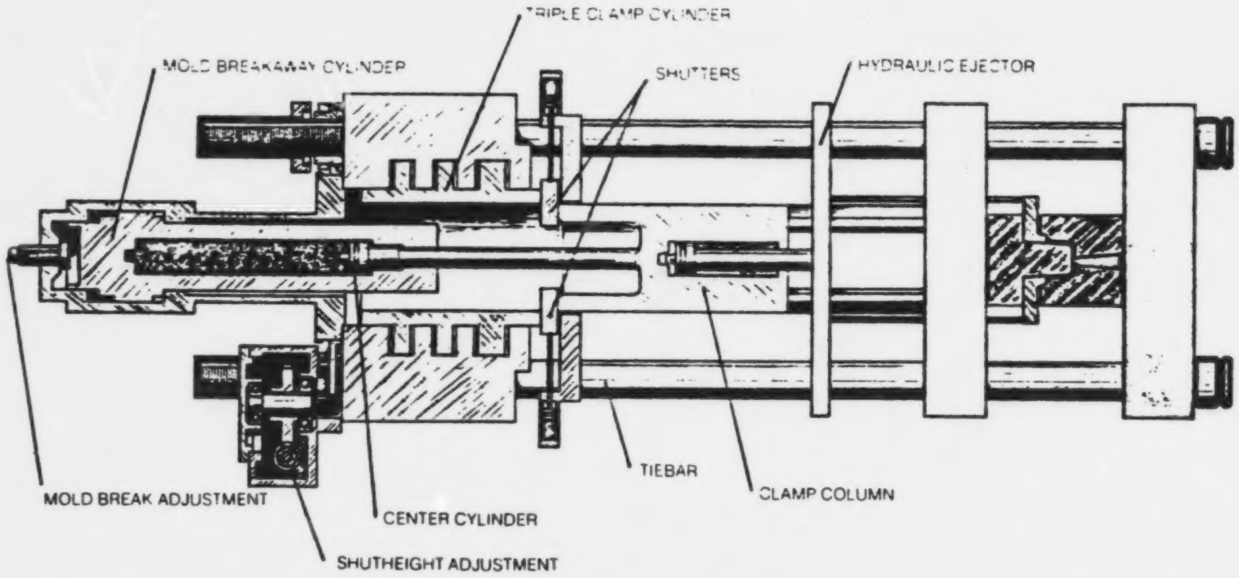
TYPICAL INJECTION MOLDING SYSTEM

Hydraulic Clamp Schematic


TRIPLE CLAMP CYLINDER
MOLD BREAKAWAY CYLINDER
SHUTTERS
HYDRAULIC EJECTOR
TIEBAR
CLAMP COLUMN
MOLD BREAK ADJUSTMENT
CENTER CYLINDER
SHUTHEIGHT ADJUSTMENT

Mold Closing - Small regenerative center cylinder advances mold at high speed.

Slow down takes place just prior to mold closing. Low closing force provides mold protection.

When mold closes, shutters move behind the clamp column.

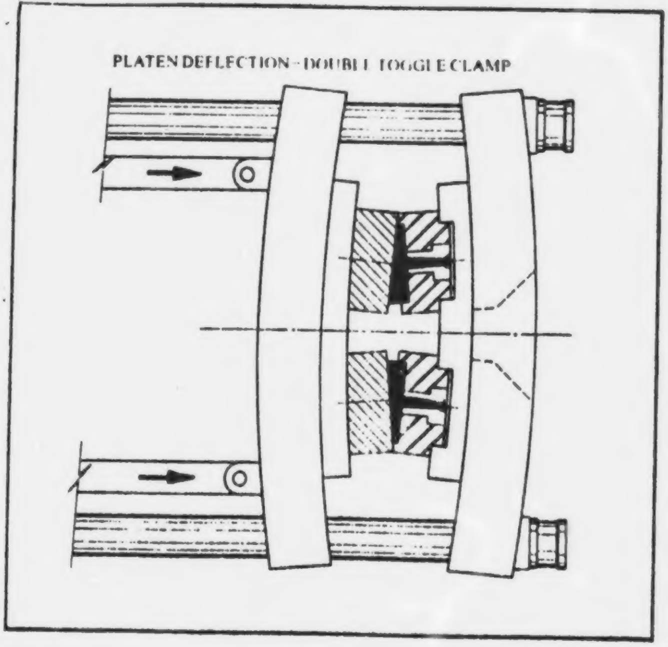
Triple hydraulic clamp cylinder then moves forward providing full clamp force.

Clamp tonnage is easily adjusted by regulating oil pressure.

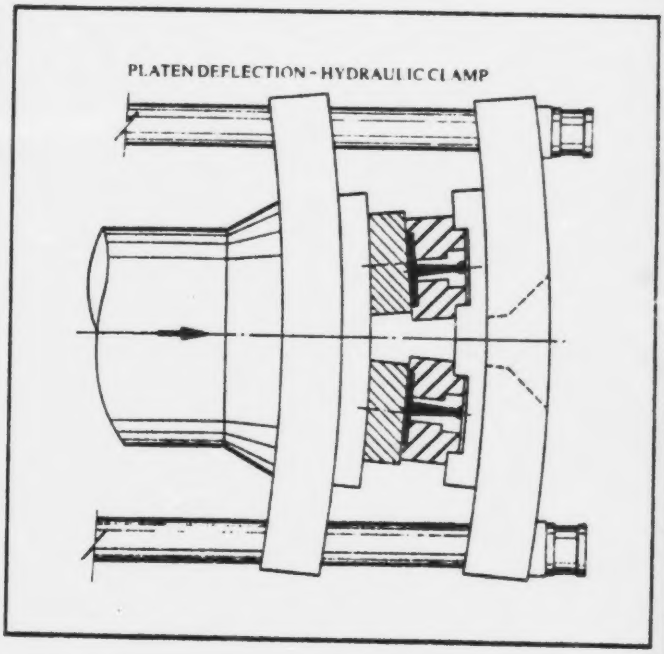
Mold Opening - Clamp cylinder is unloaded and shutters are retracted.

Clamp breakaway cylinder provides high initial opening force.

Oil is then diverted to the center cylinder, opening the mold at high speed.



PLATEN DEFLECTION - DOUBLE TOGGLE CLAMP



PLATEN DEFLECTION - HYDRAULIC CLAMP

Table . Comparison Between the Direct Clamping Method, the Toggle Method and the Compound Clamping Method

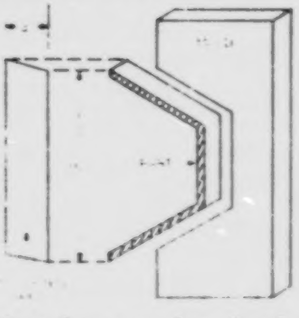
		Direct Pressure Method	Toggle Method	Compound Clamping Method
1	Clamping Stroke	Large Changes According to Mold Thickness	Small Constant Irrespective of Mold Thickness	Large
2	Speed of Movement	Generally Speaking, Slower than Toggle Method	Fast	Generally Speaking, Slower than Toggle Method
3	Mold Set-Up	Easy	Troublesome	Easy
4	Adjustment of Mold Thickness	Easy	Troublesome, Mold Thickness Adjusting Device is Required	Easy
5	Adjustment of Mold Clamping Force	Easy Checking is Possible Stable	Troublesome Checking is Difficult, Overload Likely to Occur	Easy Same as the Direct Pressure Method
6	Mold Holding Device	Effective	Sensitivity is Inferior	Effective
7	Durability	Few Worn Parts	Many Worn Parts, Lubrication Device is Required	Few Worn Parts
8	Structure	Simple	Complex	Complex
9	Oil Quantity	Large	Small	Small
10	Weight	Heavy	Medium	Light

MACHINE SIZE SELECTION

1. Projected area vs. clamping force
2. Part weight vs. machine injection capacity
3. Mold size vs. platen size
4. Mold thickness vs. closed daylight
5. Part depth vs. open daylight
6. Part depth vs. clamp stroke
7. Cycle time
8. Screw receovery vs. cycle time

Here are some general rules of thumb for selecting the right machine for molding plastic parts. These are intended as a guide only. Such things as mold and part design, and molding techniques can also affect machine size and cycle requirements. While not foolproof, these rules will help in selecting the most efficient machine size for your requirements.

Rule one.



Projected area vs. clamping force

The machine clamping force (in *tons*) must be at least:

3 times the total projected area (in *sq. in.*) of all the molded parts and runners for a complete shot. This allows 3 tons per sq. in. of projected area for parts having thin walls, deep draw or thick bosses

or

2 times the total projected area to allow 2 tons per sq. in. of projected area for parts with thick walls, shallow draw and no thick bosses.

Rule two.

Part weight vs. machine injection capacity

The total weight of parts, sprue and runner system for a complete shot should not exceed 90% of the machine's rated maximum injection capacity for the particular material molded. The requirement for a high degree of melt uniformity may further reduce the usable shot size to 75% of its rated maximum.

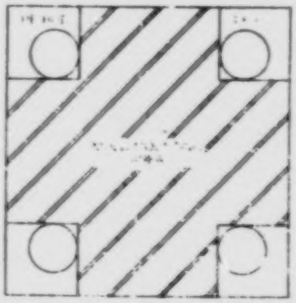
Since machines are rated in ounces of styrene, the injection capacity of the machine should be adjusted for other materials according to approximate values

To Convert oz. of Styrene	
To	**Mult. By**
[illegible]	[illegible]
[illegible]	[illegible]
ABS	[illegible]
[illegible]	1.08
[illegible]	1.3

Rule three.

Mold size vs. platen size

The mold must fit within the available mold mounting surface between the tie rods.



Rule four.

Mold thickness vs. closed daylight

Mold thickness when shut must be greater than the minimum closed daylight of the machine. For mechanical clamp machines only the mold thickness must be less than the maximum closed daylight in order to build clamp tonnage.

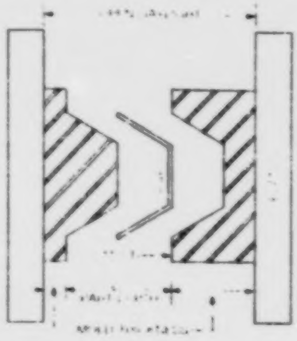
Rule five.

Part depth vs. open daylight

For part removal, open daylight must be greater than twice the depth of the part plus the thickness of the closed mold.

Equation:

Open daylight =
 2 x (part depth) + (mold thickness)



Rule six.

Part depth vs. clamp stroke

On hydraulic clamp machines the clamp stroke must be equal to or greater than the open daylight minus the mold thickness and greater than two times the depth of the molded part.

Equations:

a) Clamp stroke =
 (open daylight)−(mold thickness)
b) Clamp stroke > 2 x (part depth)

On mechanical clamp machines the clamp stroke must be equal to the open daylight minus the mold thickness and greater than 2 times the depth of the molded part.

Equations:
a) Clamp stroke =
 (open daylight)−(mold thickness)
b) Clamp stroke > 2 x (part depth)

Rule seven.

Cycle time

The cycle time equals machine time plus cooling time. Typical examples listed give approximate machine times based on minimum injection and hold time, full clamp stroke and hydraulic ejection as the mold opens. Approximate cooling times are based on general purpose plastic with the mold having adequate cooling capability and a part with uniform wall thickness.

Machine Size (tons)	Machine Time	Wall Thickness (inches)	Cooling Time
75-200	4 sec.	[illegible]	[illegible]
300-500	8 sec.	.045	5 sec.
700-1200	10 sec.	[illegible]	[illegible] sec.
1500-2500	15 sec.	.187	26 sec.

Equation:

Cycle time* =
 (machine time) + (cooling time)

*For manual part removal add 5-10 seconds.

Example:

The part to be molded has a uniform wall thickness of .045 inches and the machine selected is a Farrel 375 ton unit.

Cycle time:
 8 sec. machine time
+ 5 sec. cooling time
 13 sec. total cycle for
 automatic operation

Rule eight.

Screw recovery vs. cycle time

For minimum cycle time, screw recovery time must be equal to or less than cooling time.

Screw recovery =

$$\frac{\text{Shot Wt. (oz.)}}{\text{Recovery Rate (oz./sec.)}} \leq \text{Cooling time}$$

There is another good rule of thumb for machine selection too. Get all the facts. For free bulletins describing Farrel's complete line of hydraulic and mechanical clamp injection molding machines, write Farrel Company Division, USM Corporation, 565 Blossom Road, Rochester, N.Y. 14610.

FARREL

MOLDING PROCESSES APPLICABLE TO PLASTIC MATERIALS

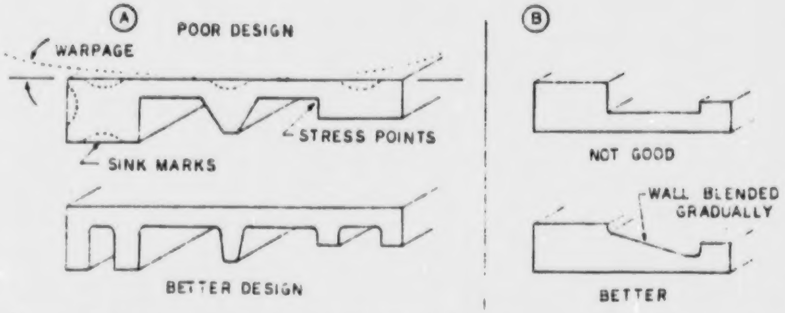
MATERIAL FAMILY	INJECTION	COMPRESSION	TRANSFER	CASTING	COLD MOLDING	COATING	STRUCTURAL FOAM	EXTRUSION	LAMINATING	SHEET FORMING	RP MOLDING FRP	FILAMENT	DIP & SLUSH	BLOW	ROTATIONAL
ABS[1]	X						X	X		X					
Acetal	X						X	X		X				X	X
Acrylic	X			X		X		X	X	X					
Alkyl		X	X	X	X	X			X			X			
ASA[1]	X						X	X		X					
Cellulosic	X					X	X	X	X	X				X	X
Epoxy		X	X	X	X	X			X			X			
Fluoroplastic	X	X	X		X	X		X		X					X
Melamine-Formaldehyde	X	X	X	X		X			X						
Nylon	X			X		X	X	X						X	X
Phenol-Formaldehyde	X	X	X	X	X	X			X						
Poly (Amide-Imide)	X	X	X					X							
Polyarylether	X							X							
Polybutadiene	X		X					X							
Polycarbonate	X	X					X	X		X				X	X
Polyester (TP)[1]	X					X		X							X
Polyester-Fiberglass (TS)[1]		X	X					X	X		X	X			X
Polyethylene	X	X				X	X	X	X	X				X	X
Polyimide	X	X				X		X (TP)[1]							
Polyphenylene Oxide	X						X	X							X
Polyphenylene Sulfide	X	X				X									
Polypropylene	X						X	X		X				X	X
Polystyrene	X						X	X		X				X	X
Polysulfone	X	X						X		X					
Polyurethane (TS) (TP)[1]	X	X	X	X		X	X	X (TP)[1]	X	X					X
San[1]	X						X	X	X	X					X
Silicone		X		X				X							
Styrene Butadiene	X					X		X	X						
Urea Formaldehyde		X							X						
Vinyl	X	X				X	X	X	X	X			X	X	X

SUGGESTED WALL THICKNESSES FOR THERMOPLASTIC MOLDING MATERIALS.

Thermoplastic Materials	Minimum (Inches)	Average (Inches)	Maximum (Inches)
Acetal	.015	.062	.125
ABS	.030	.090	.125
Acrylic	.025	.093	.250
Cellulosics	.025	.075	.187
FEP fluoroplastic	.010	.035	.500
Nylon	.015	.062	.125
Polycarbonate	.040	.093	.375
Polyester T. P.	.025	.062	.500
Polyethylene (L. D.)	.020	.062	.250
Polyethylene (H.D.)	.035	.062	.250
Ethylene vinyl acetate	.020	.062	.125
Polypropylene	.025	.080	.300
Polysulfone	.040	.100	.375
Noryl (modified PPO)	.030	.080	.375
Polystyrene	.030	.062	.250
SAN	.030	.062	.250
PVC-Rigid	.040	.093	.375
Polyurethane	.025	.500	1.500
Surlyn (ionomer)	.025	.062	.750

SUGGESTED WALL THICKNESS FOR THERMOSETTING MOLDING MATERIALS.

Thermosetting Materials	Minimum Thickness	Average Thickness	Maximum Thickness
Alkyd - glass filled	.040	.125	.500
Alkyd - mineral filled	.040	.187	.375
Diallyl phthalate	.040	.187	.375
Epoxy glass	.030	.125	1.000
Melamine - cellulose filled	.035	.100	.187
Urea - cellulose filled	.035	.100	.187
Phenolic - general purpose	.050	.125	1.000
Phenolic - flock filled	.050	.125	1.000
Phenolic - glass filled	.030	.093	.750
Phenolic - fabric filled	.062	.187	.375
Phenolic - mineral filled	.125	.187	1.000
Silicone glass	.050	.125	.250
Polyester premix	.040	.070	1.000



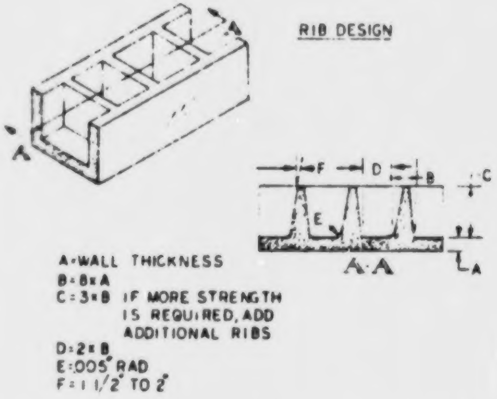
(A) Wall thickness in molded parts should be as uniform as possible to eliminate warpage, sink marks, and internal stresses. (B) If different wall thicknesses in a part cannot be eliminated they should be blended gradually.

VARIANCES IN WALL THICKNESS

As was pointed out, wall thicknesses should not be too heavy, nor should they vary greatly. Walls should not vary more than a ratio of three to one. This is true if the part is molded by either the compression or injection method and should be avoided with transfer molding as well.

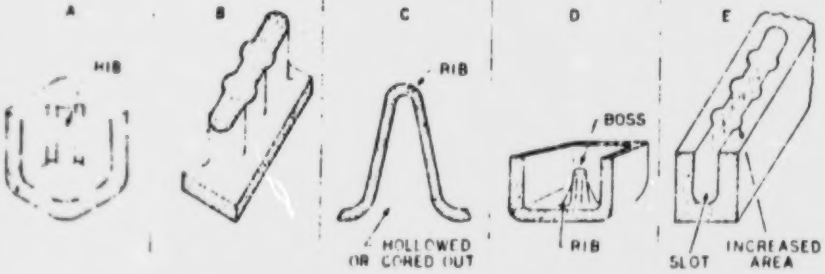
When parts are made by compression or transfer molding, the parts will remain in the mold while they are being cured. A longer cure is required for a heavy section than for a thin one. In the process of curing a heavy section of a thermosetting plastic part, the thin section may become so overheated that it will discolor, especially with urea and melamine materials.

Parts that are molded by the injection method remain in the mold until they become hard and cool. A longer time is required to cool and harden a heavy section than a thin section. If the heavy section can be reduced in thickness, the mold can produce more and better parts. Whenever a heavy section is encountered in a plastics design, that heavy section should be redesigned (Fig. 4-14). A uniform section will speed up production and give a more satisfactory part, regardless of whether thermoplastics or thermosetting materials are used.

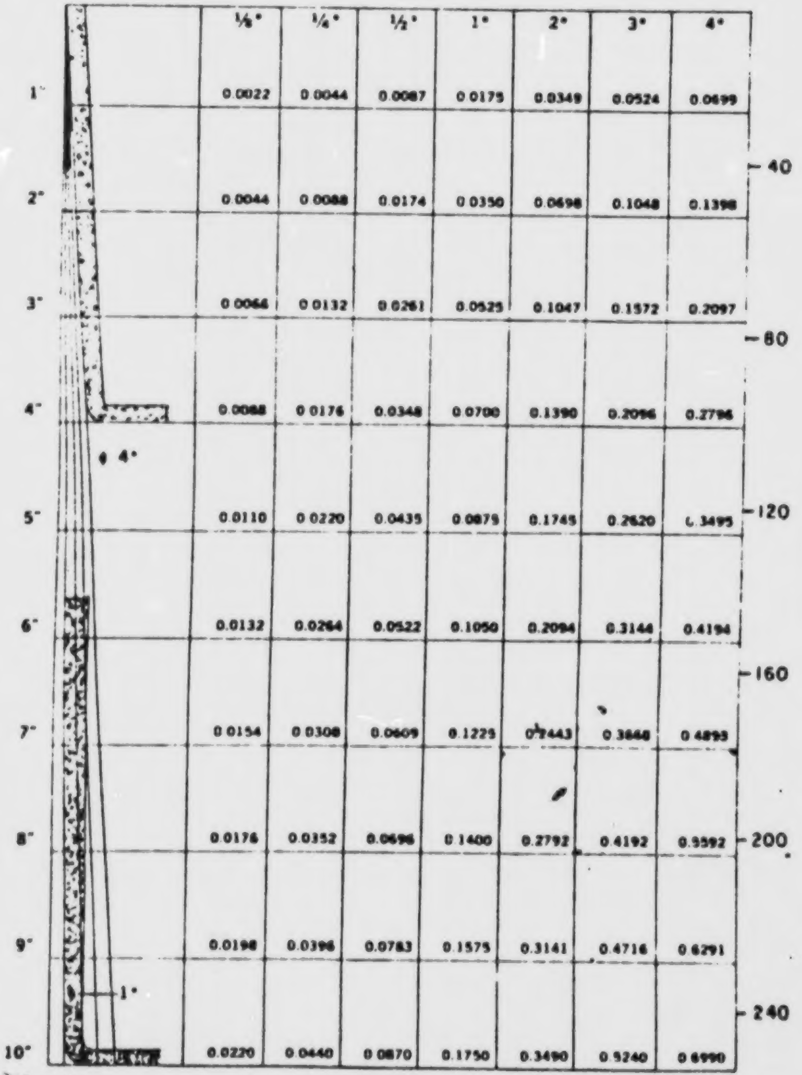

RIB DESIGN
A
A
F
D
B
C
E
A-A
A
A-WALL THICKNESS
B=.8×A
C=3×B IF MORE STRENGTH IS REQUIRED, ADD ADDITIONAL RIBS
D=2×B
E=.005" RAD
F=1 1/2° TO 2°

[redacted] This drawing illustrates the rib design and proportions used in most thermoplastic materials. *(Courtesy Dow Chemical Co.)*

[redacted] This picture illustrates the use of ribs in the making of an automobile arm rest.

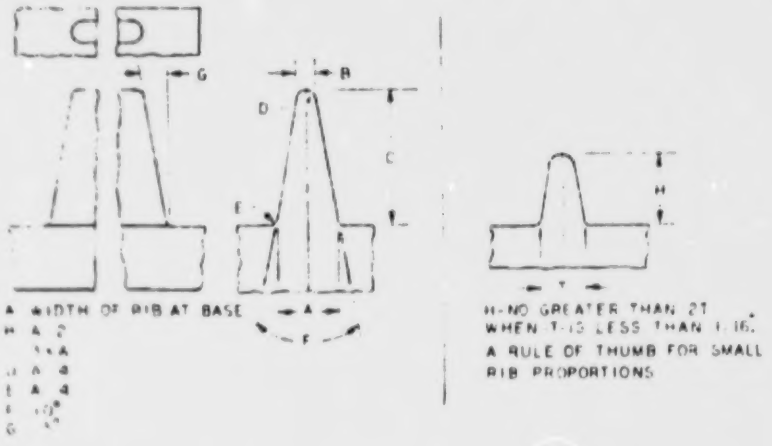

A
RIB
B
C
RIB
HOLLOWED OR CORED OUT
D
BOSS
RIB
E
SLOT
INCREASED AREA

[redacted] This illustrates some fundamental design factors for ribs. (A) A rib should be located in the corner or side of a molded part. This will lower the mold cost and allow easier filling of the plastic part. (B) Bosses and fillets will help to fill out ribs. (C) A uniform wall thickness can be maintained in a rib if it is hollowed or cored out from the back. (D) Ribs on the side of long bosses will aid in filling them. (E) Increasing the area of slots at intervals in the molded part will add strength to the mold.

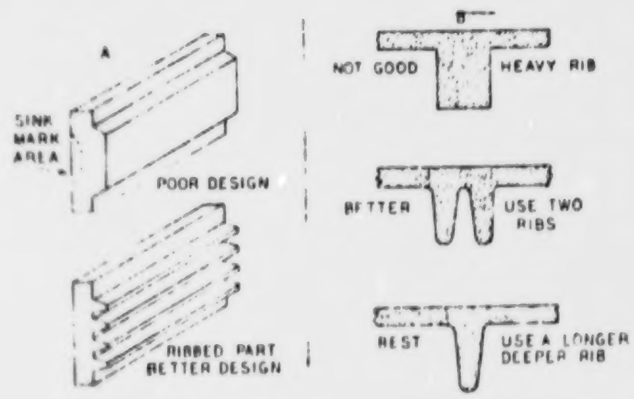

4°
1°
MILLIMETERS
40
80
120
160
200
240

	⅛°	¼°	½°	1°	2°	3°	4°
1"	0.0022	0.0044	0.0087	0.0175	0.0349	0.0524	0.0699
2"	0.0044	0.0088	0.0174	0.0350	0.0698	0.1048	0.1398
3"	0.0066	0.0132	0.0261	0.0525	0.1047	0.1572	0.2097
4"	0.0088	0.0176	0.0348	0.0700	0.1390	0.2096	0.2796
5"	0.0110	0.0220	0.0435	0.0875	0.1745	0.2620	0.3495
6"	0.0132	0.0264	0.0522	0.1050	0.2094	0.3144	0.4194
7"	0.0154	0.0308	0.0609	0.1225	0.2443	0.3668	0.4893
8"	0.0176	0.0352	0.0696	0.1400	0.2792	0.4192	0.5592
9"	0.0198	0.0396	0.0783	0.1575	0.3141	0.4716	0.6291
10"	0.0220	0.0440	0.0870	0.1750	0.3490	0.5240	0.6990

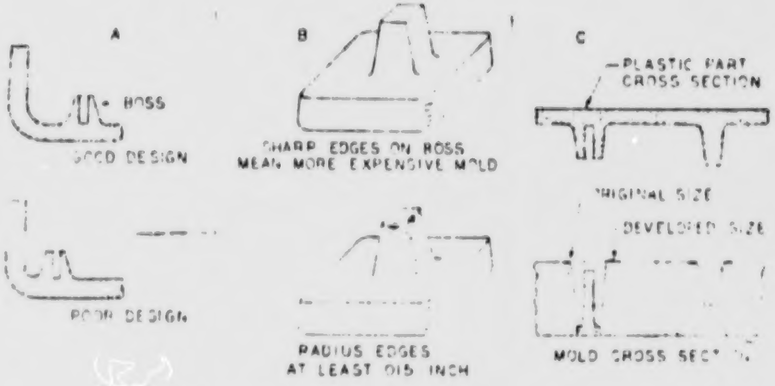
[redacted] Relation of degree of taper per side to the dimension in inch/inch. *(Courtesy Plastics Engineering Handbook)*


G
B
D
C
H
E
R
A
F
T
A WIDTH OF RIB AT BASE
B A/2
C 3×A
D A/4
E A/4
F 10°
G 5°
H-NO GREATER THAN 2T WHEN T IS LESS THAN 1/16.
A RULE OF THUMB FOR SMALL RIB PROPORTIONS

Recommended proportions for ribs molded with thermosetting materials.

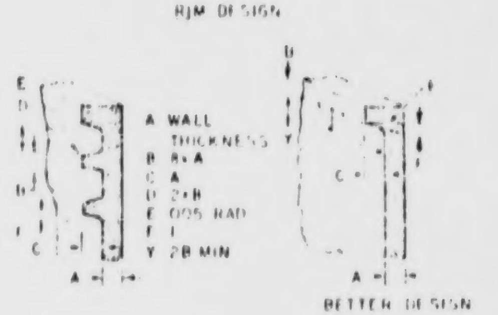

A
SINK MARK AREA
POOR DESIGN
RIBBED PART BETTER DESIGN
B
NOT GOOD
HEAVY RIB
BETTER
USE TWO RIBS
BEST
USE A LONGER DEEPER RIB

(A) In order to eliminate sink marks it is better to have many small ribs instead of one large rib as illustrated in the drawing. (B) Good rib design calls for narrow ribs instead of one large heavy rib.

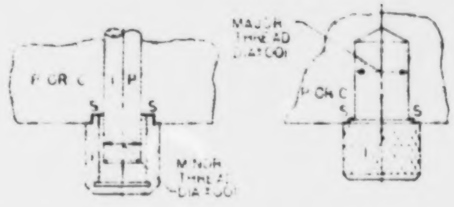

A
BOSS
GOOD DESIGN
POOR DESIGN
B
SHARP EDGES ON BOSS MEAN MORE EXPENSIVE MOLD
RADIUS EDGES AT LEAST .015 INCH
C
PLASTIC PART CROSS SECTION
ORIGINAL SIZE
DEVELOPED SIZE
MOLD CROSS SECTION

(A) Avoid, if possible, bosses too near an outside wall. This will cause wea sections in the mold. (B) Sharp edges on bosses should be avoided. (C) Close tolerances o bosses and projections can be obtained by development. This is done by designing the mo undersize then removing metal from the mold until the correct dimensions are obtained on th molded part.

mold, as the part cannot be stripped out normally. Loose sections in the mold must be used and the mold cost is approximatley 40% more than a conventional mold. The same or almost equivalent strength can be achieved by using gussets.


RIM DESIGN
E
D
B
F
C
A
A WALL THICKNESS
B B×A
C A
D 2×B
E .005 RAD
F 1
Y 2B MIN
Y
C
BETTER DESIGN

This drawing illustrates design and proportions of a rim. A better part can b obtained by using gussets. This design is used in most thermoplastic materials. (Courtesy Dow Chemical Co.)



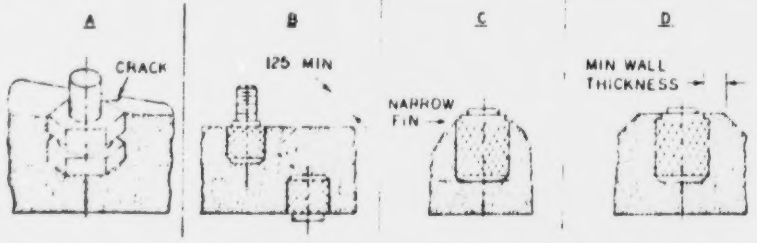
Shoulders or seals are always flush or contact a portion of the mold. P or C, plunger or cavity. IP, insert pin. I, insert. S, sealing surface, shown heavy.

close tolerance makes a tight fit or seal between the threads on the insert and the locating pin in the mold.

Male inserts molded without any sealing shoulders should have a tolerance of plus or minus 0.001 in. on the major diameter, in order to help prevent material from flashing into the threads on the insert and locating pin in the mold.

CRACKING AT THE INSERTS

Metal inserts molded in either thermosetting or thermoplastic material require a wall of compound around them of sufficient thickness to prevent cracking upon alternate heating and cooling and aging of the part. Table 7-1 gives what is considered the minimum wall thickness requirements for both the thermoplastics and thermosetting compounds. In some cases, an insert with sharp embedded corners is molded in the plastic. Sharp corners increase the danger of cracking through the wall (Fig. 7-20a).



[illegible] (A) Inserts with sharp corners should be avoided. Such inserts may cause cracking of the part. (B) Inserts molded in opposite sides of a thermosetting part should be no closer than 0.125 inch. (C) Avoid bringing a boss down to a narrow fin around an insert. This may cause cracking of the plastic material. (D) Inserts molded in bosses should have enough compound around them to prevent cracking. Minimum wall thickness can be obtained from Table 7-1.

Inserts that are molded in opposite sides of a thermosetting part should be no closer than 0.125 in. (Fig. 7-20b). Cracking of the compound between the inserts may occur if they are closer. If inserts molded in this position carry electrical current, they may short circuit through the crack.

If a boss supporting insert is required, it may be necessary to bring the boss down to a narrow fin around the insert (Fig. 7-20c). This is to be avoided. The same results may be accomplished by cutting the

[illegible] SUGGESTED MINIMUM PLASTICS WALL THICKNESS FOR INSERTS OF VARIOUS DIAMETERS.

DIAMETER OF INSERTS						
INCHES	125	.250	375	.500	.750	1.00
PLASTIC MATERIALS						
ABS	.125	.250	.375	.500	750	1.00
Acetal	.062	.125	.187	250	.375	.500
Acrylics	.093	.125	.187	250	.375	.500
Cellulosics	.125	.250	.375	.500	750	1.00
Ethylene vinyl acetate	.040	.085	N.R.	N.R.	N.R.	N.R.
F.E.P. (fluorocarbon)	.025	.060	N.R.	N.R.	N.R.	N.R.
Nylon	.125	.250	.375	.500	.750	1.00
Noryl (modified PPO)	.062	125	.187	.250	375	500
Polyallomers	.125	250	.375	500	750	1.00
Polycarbonate	.062	125	.187	.250	.375	.500
Polyethylene (H.D.)	.125	250	.375	.500	.750	1.00
Polypropylene	.125	.250	375	.500	750	1.00
Polystyrene	Not Recommended					
Polysulfone	Not Recommended					
Surlyn (ionomer)	.062	.093	125	187	250	.312
Phenolic G.P.	.093	156	187	.218	.312	.343
Phenolic (medium impact)	.078	140	156	203	281	.312
Phenolic (high impact)	.062	125	.140	187	.250	281
Urea	.093	.156	187	.218	312	.343
Melamine	125	.187	218	.312	.343	375
Epoxy	.020	.030	.040	.050	.060	.070
Alkyd	125	187	187	312	.343	.375
Diallyl phthalate	125	187	250	.312	.343	.375
Polyester (premix)	.093	125	140	187	.250	281
Polyester T.P.	.062	125	187	250	.375	375

STANDARDS AND PRACTICES OF PLASTICS CUSTOM MOLDERS

Engineering and Technical Standards

LOW DENSITY POLYETHYLENE

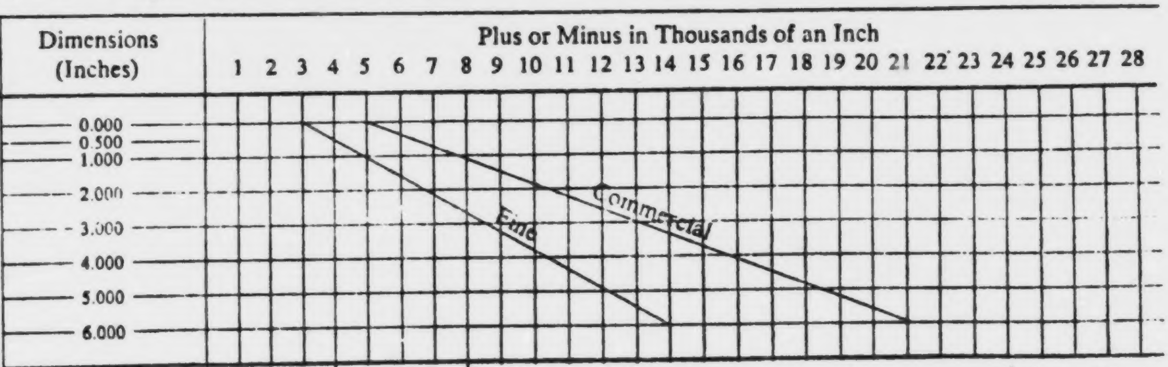
NOTE: The Commercial values shown below represent common production tolerances at the most economical level. The Fine values represent closer tolerances that can be held but at a greater cost.

Drawing Code

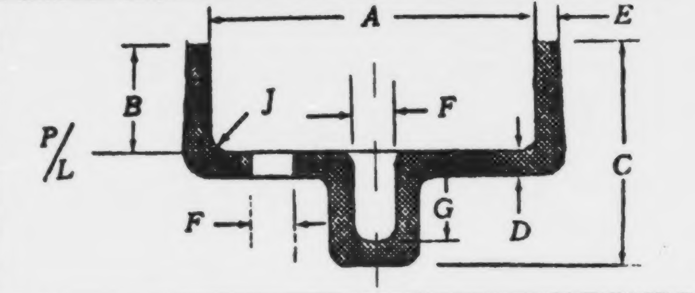
A = Diameter (see Note #1)

B = Depth (see Note #3)

C = Height (see Note #3)



Drawing Code	Dimensions (Inches)	Comm. ±	Fine ±
	6.000 to 12.000 for each additional inch add (inches)	.005	.004
D=Bottom Wall (see Note #3)		.005	.004
E = Side Wall (see Note #4)		.005	.004
F = Hole Size Diameter (see Note #1)	0.000 to 0.125	.003	.002
	0.125 to 0.250	.004	.003
	0.250 to 0.500	.005	.004
	0.500 & Over	.006	.005
G = Hole Size Depth (see Note#5)	0.000 to 0.250	.003	.003
	0.250 to 0.500	.004	.004
	0.500 to 1.000	.006	.005
Draft Allowance per side (see Note #5)		2°	1°
Flatness (see Note #4)	0.000 to 3.000	.020	.015
	3.000 to 6.000	.030	.020
Thread Size (class)	Internal	1	2
	External	1	2
Concentricity (see Note #4)	(T.I.R.)	.010	.008
Fillets, Ribs, Corners (see Note #6)		.025	.010
Surface Finish	(see Note #7)		
Color Stability	(see Note #7)		



REFERENCE NOTES

1 – These tolerances do not include allowance for aging characteristics of material.

2 – Tolerances based on ⅛" wall section.

3 – Parting line must be taken into consideration.

4 – Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is impossible to achieve.

5 – Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.

6 – These values should be increased whenever compatible with desired design and good molding technique.

7 – Customer-Molder understanding necessary prior to tooling.

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SPECIAL MATERIAL CONSIDERATIONS

For the user of a selection guide to fully utilize the data available, it is desirable to develop a familiarity with the physical and mechanical behavior of plastics. An understanding of the general mechanical behavior of plastics is most important. B. S. Benjamin [1]* list. nine important points to consider.

1. The stress/strain curve of plastics is not usually linear up to yield. In some cases the yield may be very slight or not at all.

2. The modulus of elasticity in tension of plastics is not necessarily the same as that in compression.

3. The modulus of elasticity of plastics is very low compared to metals.

4. Plastics can exhibit anisotropic behavior.

5. The mechanical behavior of plastics is affected by the rate of straining of the material.

6. The mechanical behavior of plastics is affected by temperature and time.

7. Compared to metals, plastics creep considerably under load with time.

8. Plastics show a reduction in ultimate strengths with time, even under static loading.

9. The properties of plastics can be affected by environmental conditions.

In addition, the effects of heat, fillers and glass reinforcements must be thoroughly understood and used when specifying properties.

Where long-term heat resistance is a problem, it is important to search material supplier data for long-term properties or to develop them through testing.

Use of fillers and glass reinforcements in plastics further compounds the problem, because there is an infinite number of possible mixtures, it is impossible to list all of the various materials. In general, with increasing glass or filler content, the effects upon the properties of any plastic are as follows:

- Higher tensile strength.
- Lower elongation.
- Poorer wear resistance. Some fillers in bearing materials tend to improve wear resistance. Glass usually reduces wear resistance because of the abrasiveness of the glass once exposed to the wearing surface.
- Higher flexural strength.
- Impact strength is affected variably.
- Higher heat deflection temperature.
- Lower thermal expansion.
- Becomes more opaque.

Glass fibers and fillers have little or no effect on the following properties.

- Hardness — unless very highly filled.
- Electrical properties.
- Chemical resistance.
- Weatherability.

MATERIAL SELECTION PROCEDURE

The material selection procedure includes three steps:

I — APPLICATION SCREENING

II — GENERIC FAMILY AND SPECIFIC GRADE IDENTIFICATION

III — PROCESS SELECTION AND COST ANALYSIS

STEP I — APPLICATION SCREENING

The first step in using the plastic material selection guide is to determine if plastics should be

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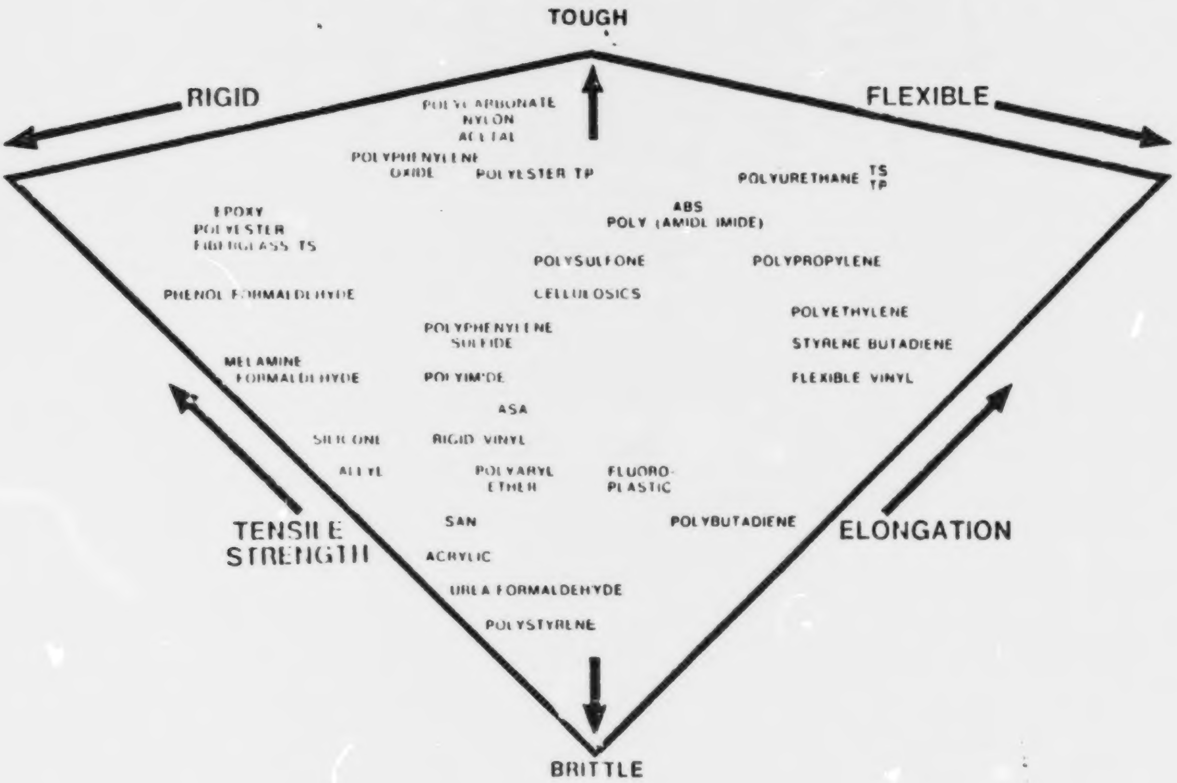
*Numbers appearing in brackets refer to references at end of this report.

CHART 8. QUALITATIVE SELECTION CHART


TOUGH
RIGID
FLEXIBLE
POLYCARBONATE
NYLON
ACETAL
POLYPHENYLENE OXIDE
POLYESTER TP
POLYURETHANE TS TP
EPOXY
POLYESTER
FIBERGLASS TS
ABS
POLY (AMIDE IMIDE)
POLYSULFONE
POLYPROPYLENE
PHENOL FORMALDEHYDE
CELLULOSICS
POLYETHYLENE
POLYPHENYLENE SULFIDE
STYRENE BUTADIENE
MELAMINE FORMALDEHYDE
POLYIMIDE
FLEXIBLE VINYL
ASA
SILICONE
RIGID VINYL
ALLYL
POLYARYL ETHER
FLUORO-PLASTIC
TENSILE STRENGTH
SAN
POLYBUTADIENE
ELONGATION
ACRYLIC
UREA FORMALDEHYDE
POLYSTYRENE
BRITTLE

SECTION 3 THE RELATIONSHIP OF PART DESIGN, MOLDING CONDITIONS, RESIN SELECTION AND MOLD DESIGN

The performance of molded parts in end use applications is influenced by

- Part Design
- Molding Conditions
- Resin Selection
- Mold Design

Factors in each of these four areas are interrelated and for an application to be successful, the relationship between them must be considered and taken into account. See Figure 5 for a listing of some of these factors. The following examples partially illustrate the importance of considering these relationships.

[illegible]

Part Design

Properties:
- Mechanical
  - (Toughness, etc.)
- Thermal
- Chemical
- Electrical
- Dimensional Stability
- Sunlight

Bearing Areas

Ribs

Bosses

Sharp Corners & Radii

Undercuts

Section Thickness

Surface Finish

Tolerances

Gate Size/Location

Molding Conditions

Process Control:
- Melt/Mold Temperature
- Cycle
- Pressure
- Ram Speed
- Materials Handling
- Use of Regrind

Effects of Molding:
- Toughness
- Mold Shrinkage
- Weld Lines
- Post Mold Shrinkage
- Part Surface

Post Molding Operations:
- Quality Control
- Moisture Conditioning
- Annealing
- Finishing
- Assembly

Resin Selection

Properties:
- Mechanical
  - (Toughness, etc.)
- Thermal
- Chemical
- Electrical
- Dimensional Stability

Processing:
- Flow
- Mold Shrinkage
- Ejectability
- Cycle

Mold Design

Gate size, location, type

Runner/Cavity layout

Draft Angles

Undercuts

Tolerances

Mold Shrinkage

Location of parting line

Vent size and location

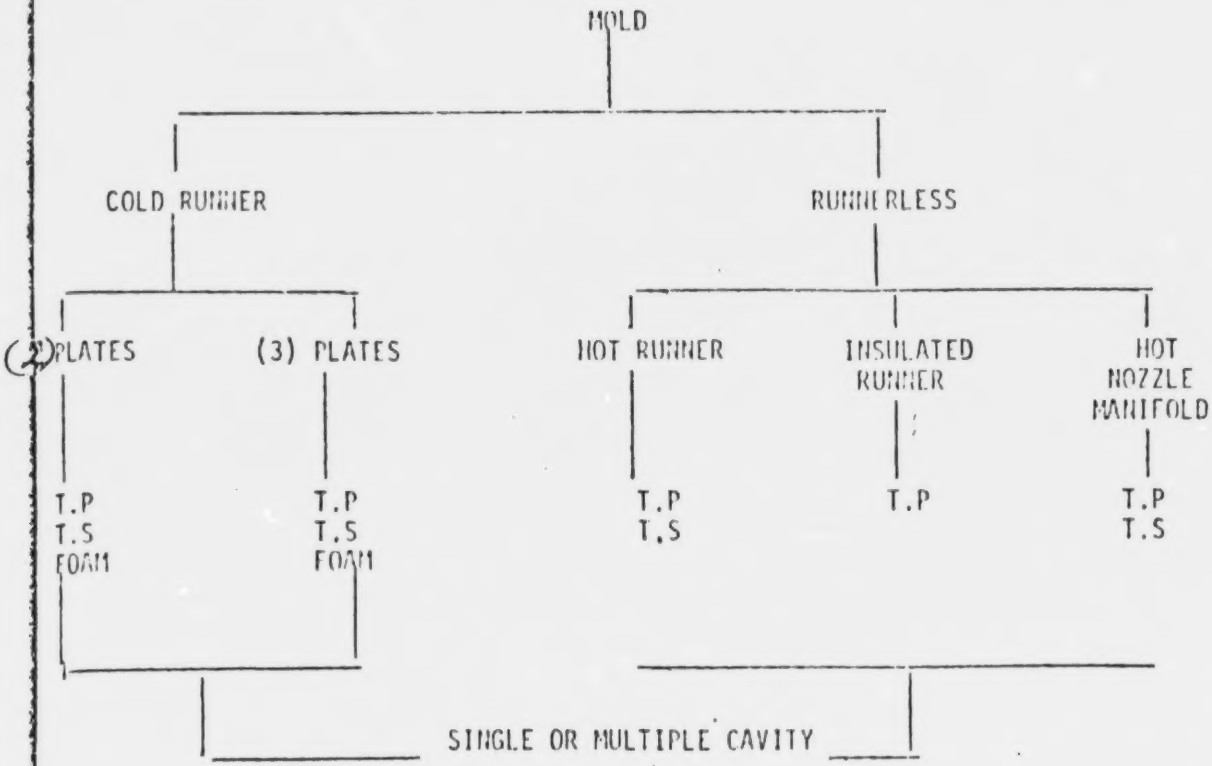
Side actions

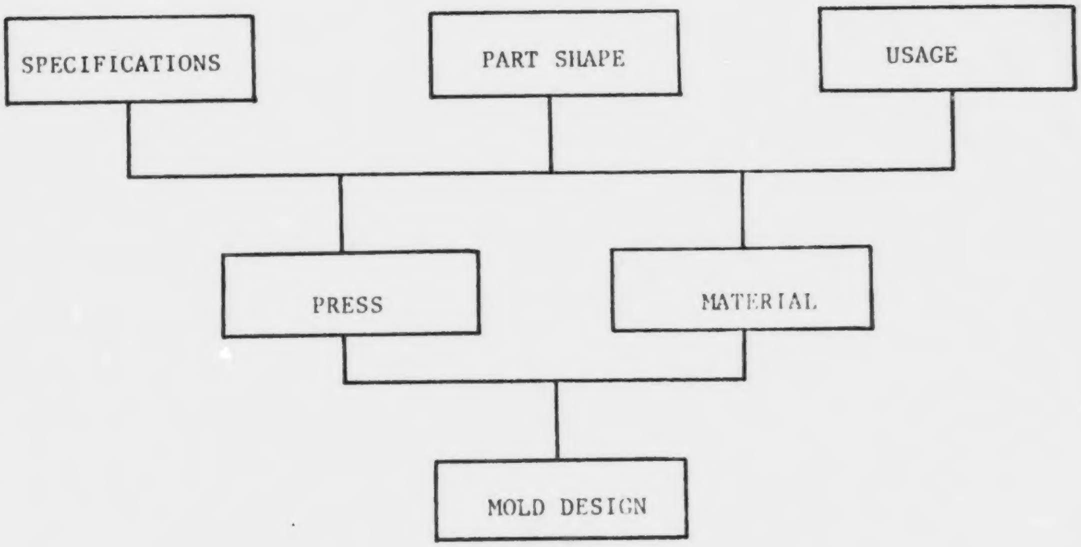
Surface finish

Coring for water cooling

INJECTION MOLDING

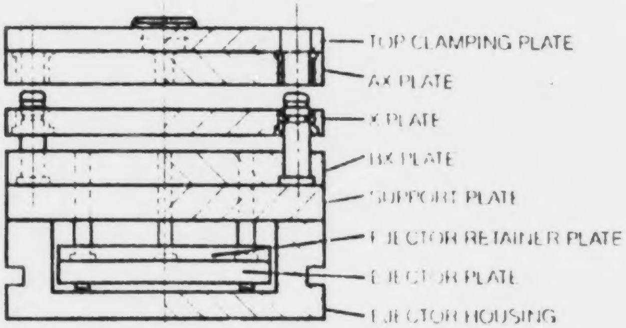
MOLD TYPES


MOLD
COLD RUNNER
RUNNERLESS
(2) PLATES
(3) PLATES
HOT RUNNER
INSULATED RUNNER
HOT NOZZLE MANIFOLD
T.P
T.S
FOAM
T.P
T.S
FOAM
T.P
T.S
T.P
T.P
T.S
SINGLE OR MULTIPLE CAVITY

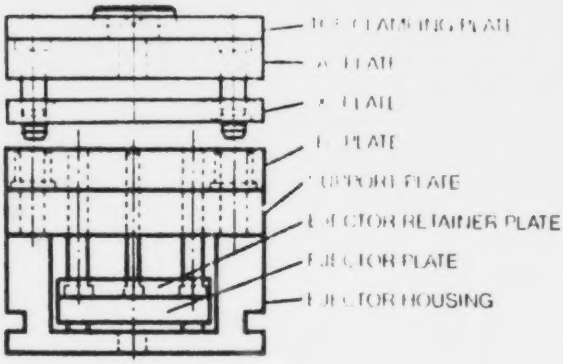

SPECIFICATIONS
PART SHAPE
USAGE
PRESS
MATERIAL
MOLD DESIGN

DECISION-MAKING PROCESS IN MOLD DESIGN.

A)-STANDARD STRIPPER PLATE MOLD ASSEMBLY.


TOP CLAMPING PLATE
AX PLATE
X PLATE
BX PLATE
SUPPORT PLATE
EJECTOR RETAINER PLATE
EJECTOR PLATE
EJECTOR HOUSING

B)-FLOATING PLATE AT THE INJECTION SIDE OF THE MOLD.


TOP CLAMPING PLATE
A PLATE
X PLATE
B PLATE
SUPPORT PLATE
EJECTOR RETAINER PLATE
EJECTOR PLATE
EJECTOR HOUSING

ADVANTAGES & DISADVANTAGES
(TWO PLATES VS. THREE PLATES)

Two Plates Mold

- cheaper to build than (3) plates mold
- more expensive to operate (part vs. runner)
- limited to side gating the part
- cycle time affected by runner system filling
- flow pattern limitation

Three Plates Mold

- permits automatic separation of parts vs. runner
- possibility of mold programming for discharging parts & runner (different container)
- limited to top gating of parts
- about 30% more expensive than two plates mold
- cycle time affected by material filling in runner
- flow pattern limitation

RUNNERLESS MOLD
(COMPARISON)

Hot Runner Mold

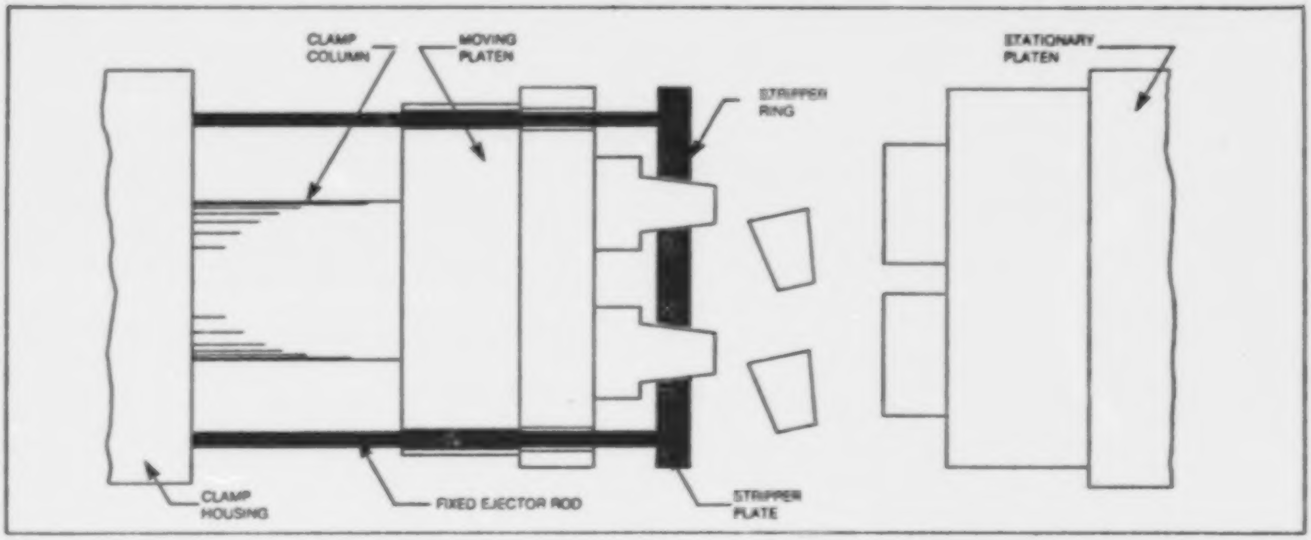
- the hot runner system becomes extension of the machine
- the material remains molted from nozzle to runner plate and permits better capacity and better flow
- heat manifold has to be same temperature as the material coming in to prevent material degrading
- no chill wall exists
- melt thermocouple to be put in the runner stream opposite to nozzle
- good mold for thermoset material but manifold temperature is very critical to not cure material and break runner plate
- automatic operation
- about 35% more expensive than three plates mold
- with thermoset, the cure happens in the mold by heat and with thermoplastics, by removing heat
- by design nature of this mold it is difficult to gate elsewhere but it is possible to gate at edge by a special system
- good for very high production 100,000 K parts

Insulated Runner

- insulation by means of material frozen layer around runner plates wall which make thermo-equilibrium
- must produce continuously to prevent runner freezing
- each gate needs a heat probe to prevent gate freezing
- about same cost as for hot runner mold

Ejector Actuation

The method of actuating the ejection mechanism is to some degree influenced by mold design and will have a bearing on machine selection.

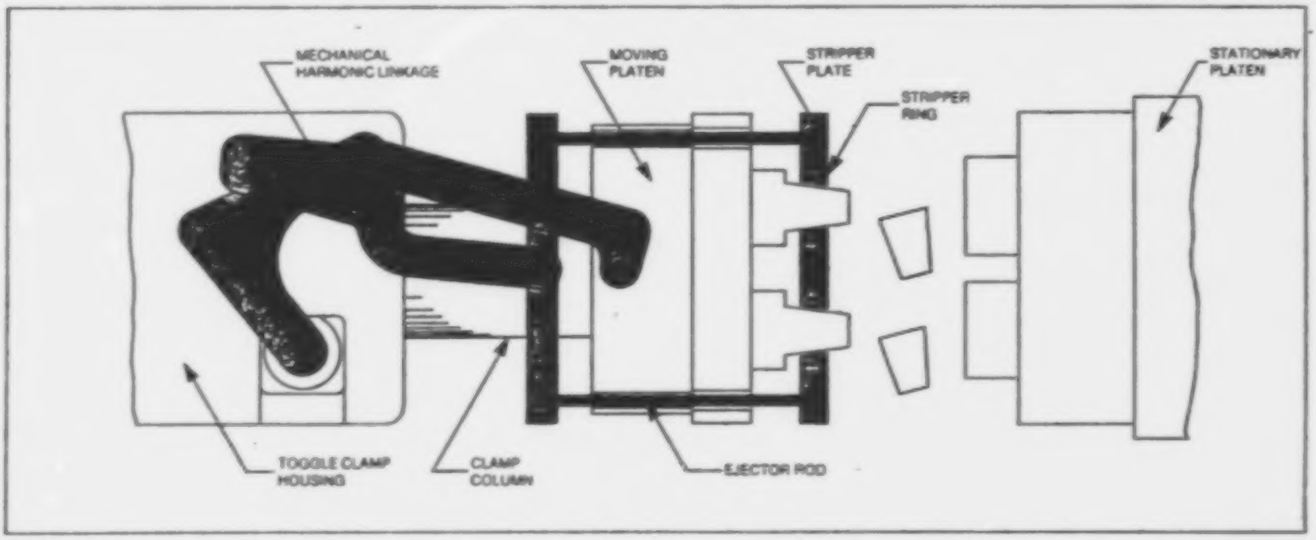

CLAMP COLUMN
MOVING PLATEN
STATIONARY PLATEN
STRIPPER RING
CLAMP HOUSING
FIXED EJECTOR ROD
STRIPPER PLATE

Mechanical Ejection

This approach uses fixed rods mounted on the clamp housing. As the mold opens, the stripper plate hits the stationary rods causing parts to be stripped from cores.

An economical method but it creates noise when stripper plate hits rods.

Recommended for either slow clamp speeds of very short ejection stroke.


MECHANICAL HARMONIC LINKAGE
MOVING PLATEN
STRIPPER PLATE
STRIPPER RING
STATIONARY PLATEN
TOGGLE CLAMP HOUSING
CLAMP COLUMN
EJECTOR ROD

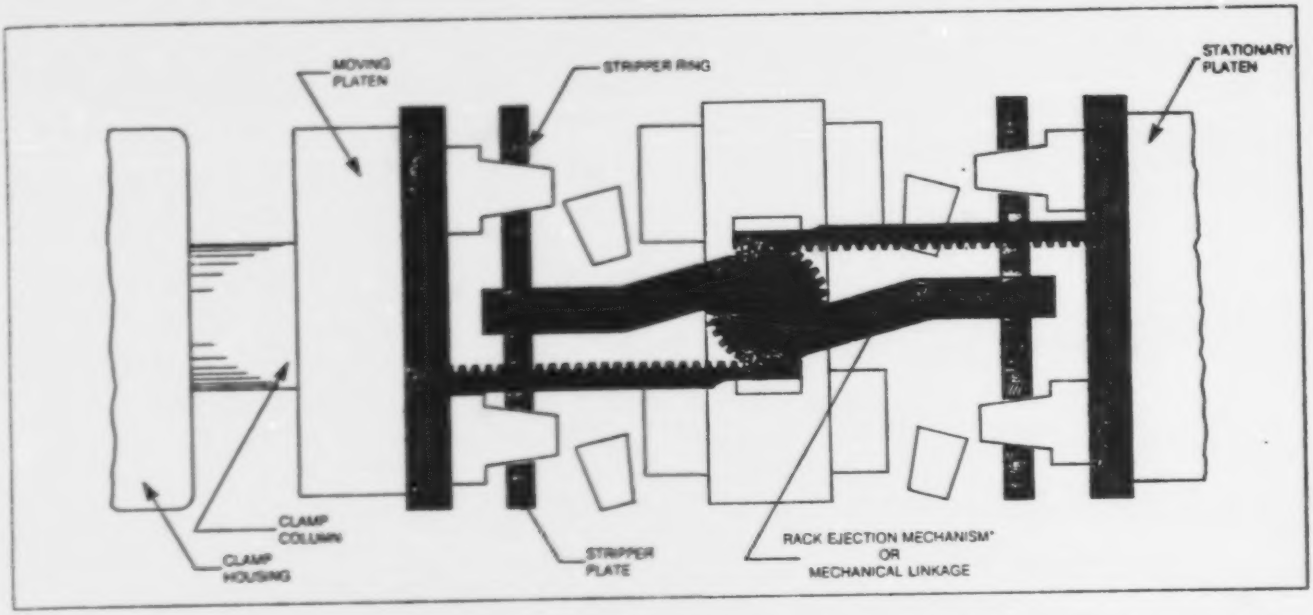
Machine Harmonic Ejection*

A simple mechanical linkage is mounted on the machine clamp housing and connected to the moving platen and ejector plate. As the mold opens, the lever action moves the ejector plate forward in time with the moving platen.

Rods fastened to the ejector plate move the mold stripper plate forward, ejecting the parts.

During the closing stroke, ejector plate returns to its normal position, usually by an air cylinder before the mold is fully closed.

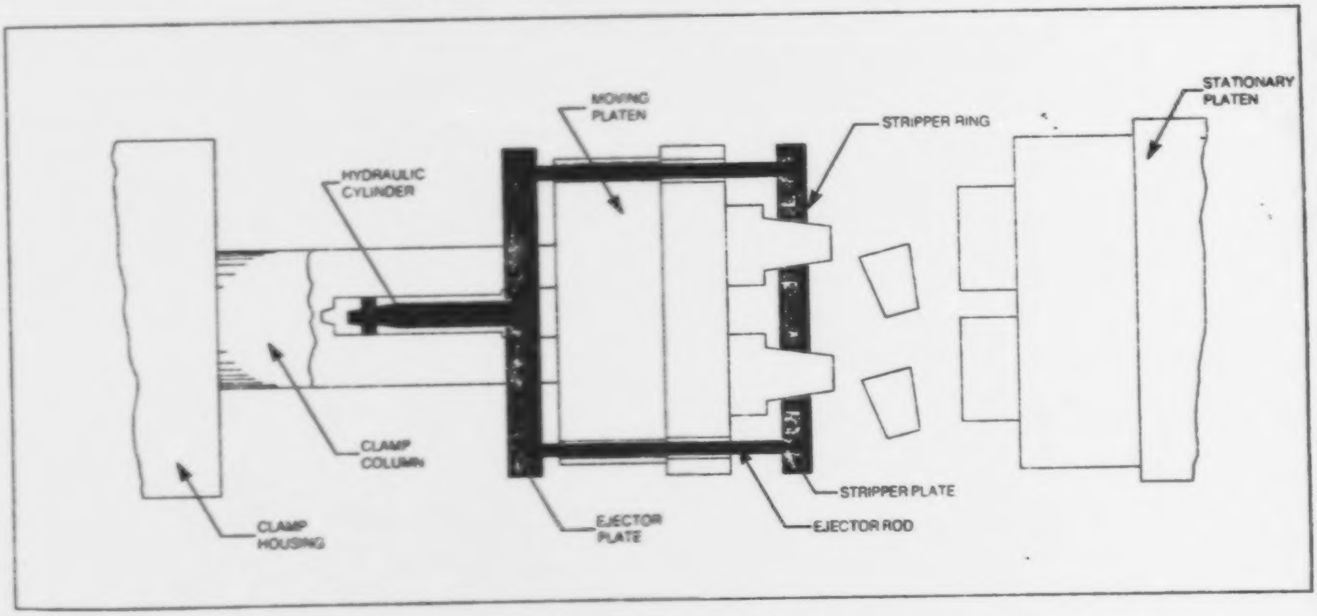
The simple mechanical design of the system is well suited to fast cycle molding.


MOVING PLATEN
STRIPPER RING
STATIONARY PLATEN
CLAMP COLUMN
CLAMP HOUSING
STRIPPER PLATE
RACK EJECTION MECHANISM*
OR
MECHANICAL LINKAGE

Stack Mold Harmonic Ejection*

In this case, the mechanical linkage provides the control of the centre section of the stack mold during the opening and closing stroke, as well as the motion of the two stripper plates in the mold to eject the parts.

This is the simplest and easiest way of achieving these two functions when required with stack molds.


MOVING PLATEN
STRIPPER RING
STATIONARY PLATEN
HYDRAULIC CYLINDER
CLAMP COLUMN
CLAMP HOUSING
EJECTOR PLATE
STRIPPER PLATE
EJECTOR ROD

Hydraulic Ejection

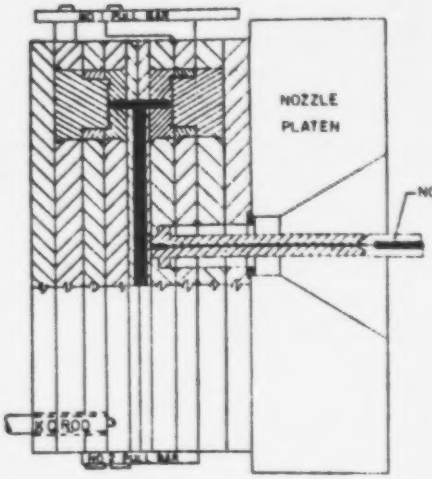
A hydraulic cylinder operates the machine ejector plate during the mold opening stroke.

Ejector rods fastened to the ejector plate operate the mold stripper plate. They can either push the stripper plate forward only, in which case it would be returned to its home position by an air cylinder, or be mechanically fastened to the stripper plate so that it is moved forward and back by the ejector plate.

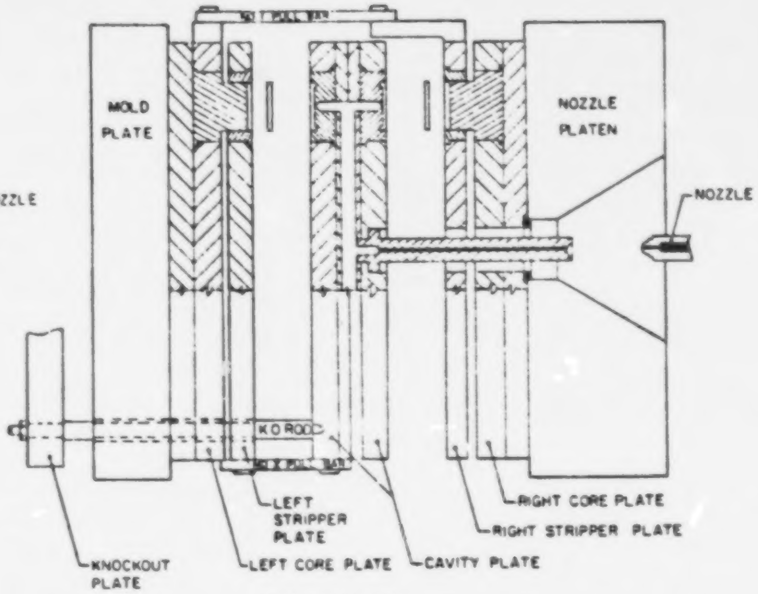
Hydraulic ejection provides the maximum flexibility for length of stroke, ejection force, speed and time of ejection.

This is recommended for general purpose use, but should not be used for cycles of more than 10 shots per minute.

SPECIAL INSTRUCTIONS FOR STACK MOLDS


NOZZLE
PLATEN
NOZZLE
K O ROD
KO 2 PULL BAR

STACK MOLD CLOSED


MOLD
PLATE
NOZZLE
PLATEN
NOZZLE
K O ROD
KO 2 PULL BAR
KNOCKOUT
PLATE
LEFT
STRIPPER
PLATE
LEFT CORE PLATE
CAVITY PLATE
RIGHT CORE PLATE
RIGHT STRIPPER PLATE

STACK MOLD OPEN

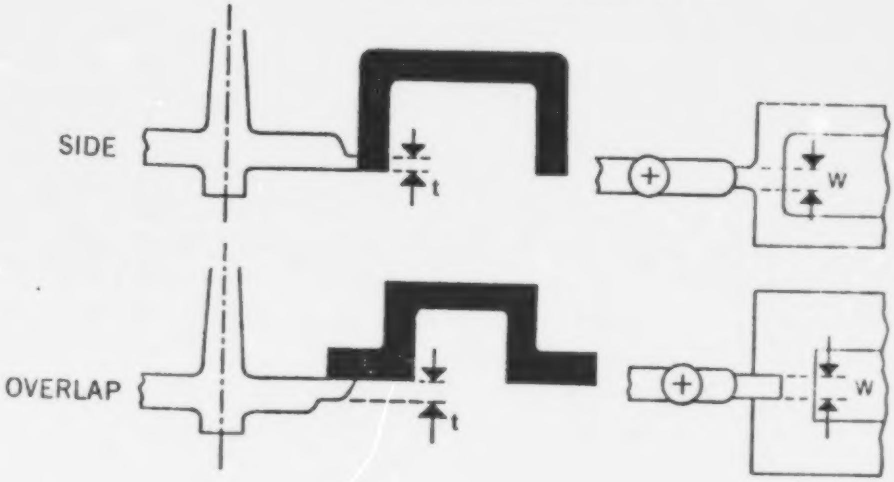
STACK MOLD OPENING AND CLOSING

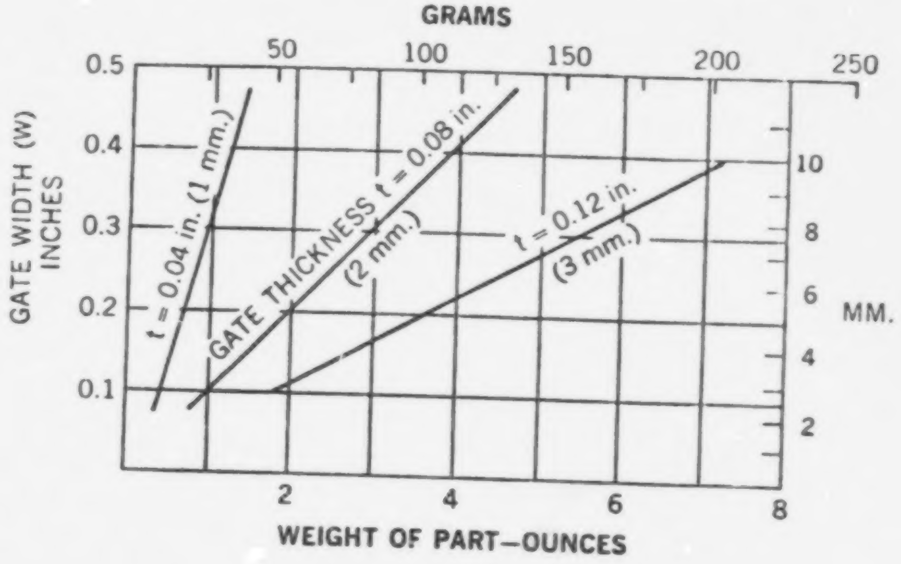
1. After injection, the mold plate, left core plate and stripper plate are retracted.
2. When end of slotted pull bar (2) contacts pin in left cavity plate, both cavity plates are pulled away from the right stripper plate.
3. Knockout takes place when the mold is nearly open. The knockout cylinder is extended so that cavity plates make pull bar (2) pull on the left stripper plate and eject parts on the left side of the mold. Molded pieces are ejected from the right side of the mold when the end of the slotted pull bar (1) contacts the pin in the right stripper plate.
4. Knockout cylinder retraction occurs after ejection, closing the left side of the mold before the clamp closes.
5. Mold bushing and nozzle contact occurs just as the mold closes and the clamp toggles to complete the cycle.

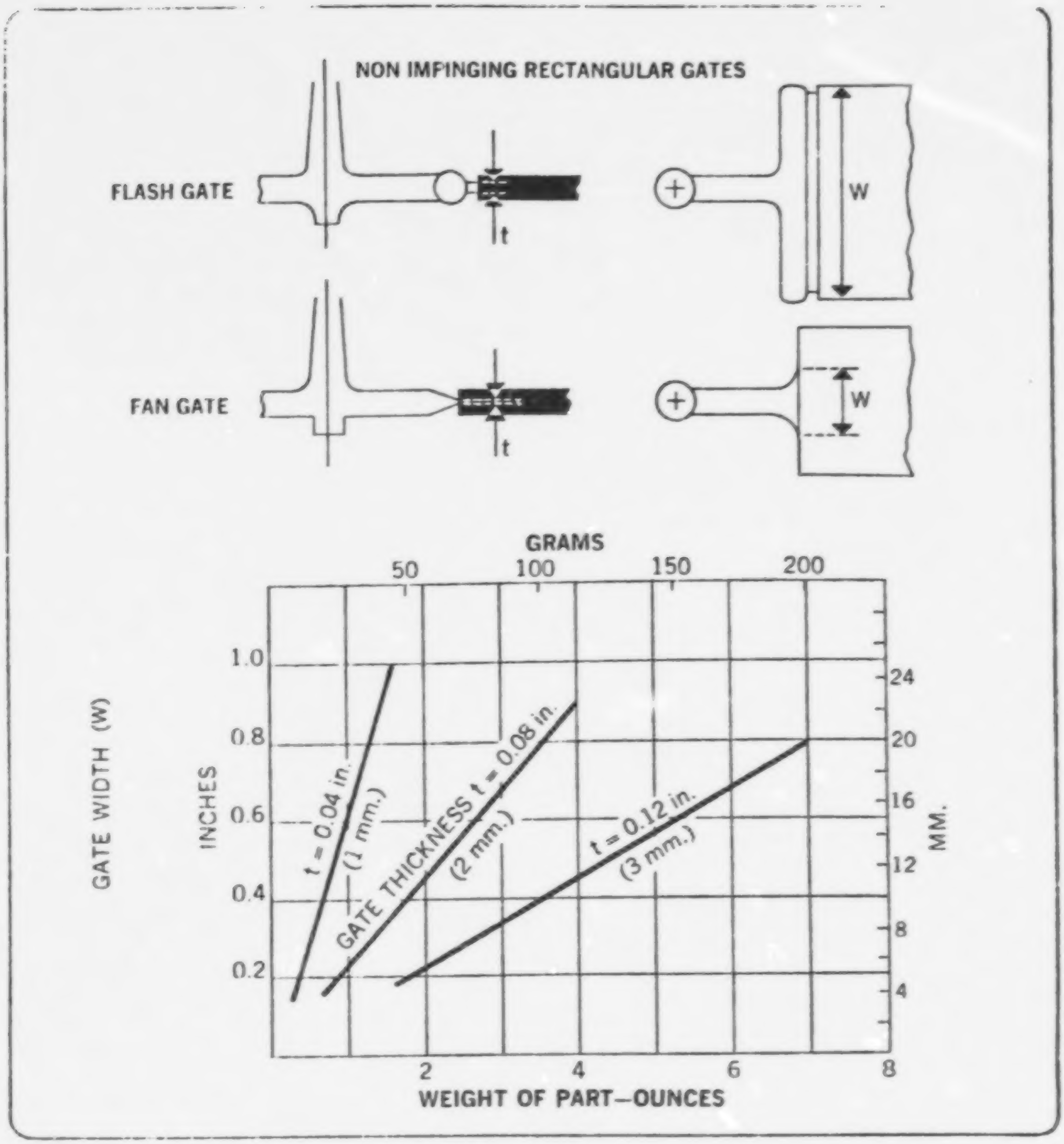
INSTALLATION OF ADJUSTABLE CARRIAGE STOP

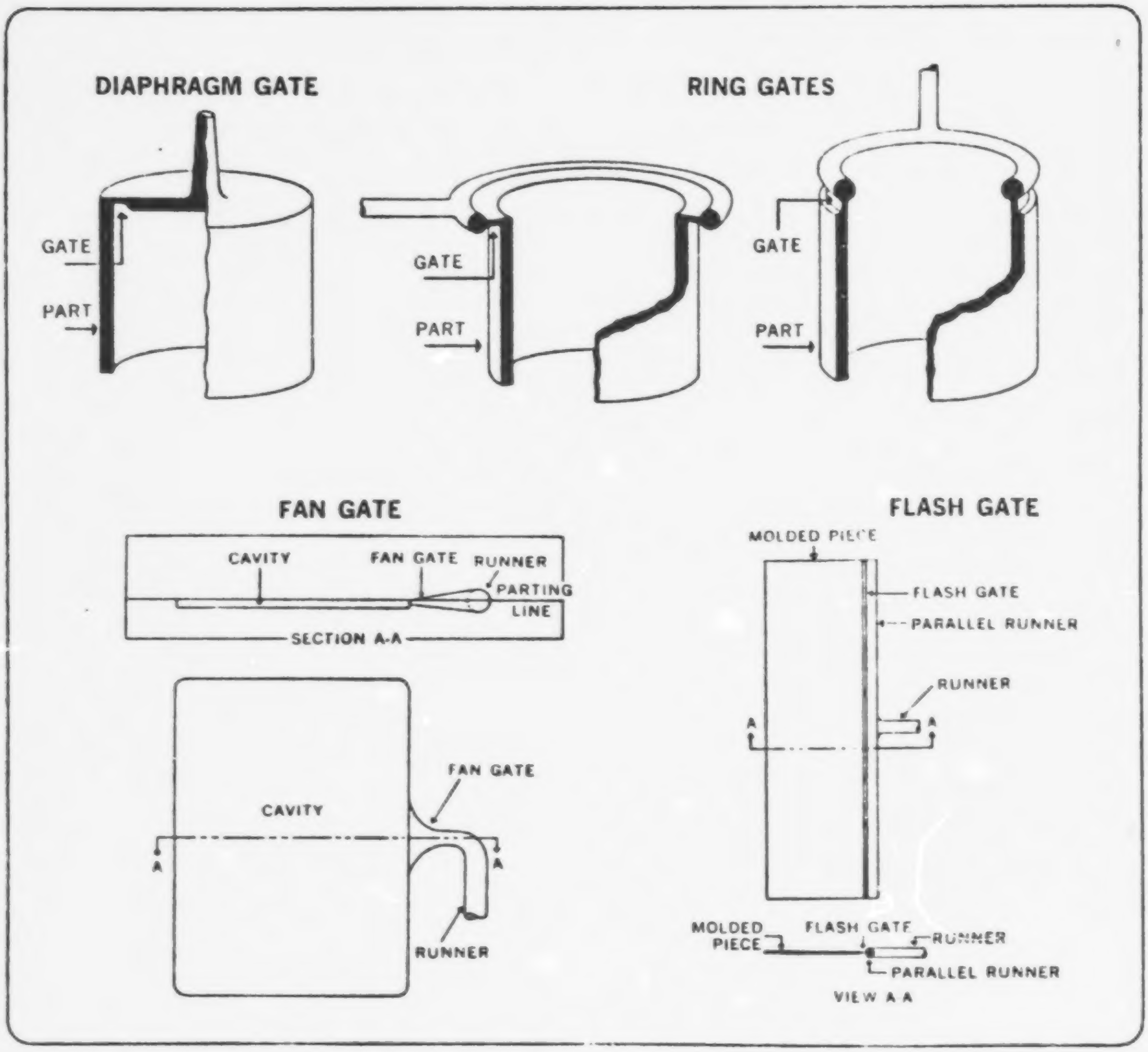
1. Make up an adjustable carriage stop. An adjustable stop must be used because the correct stopping point changes with changes in operating temperatures of the machine. Contact Impco for instructions for making a carriage stop.
2. Install mold and make clamp toggle adjustments.
3. With clamp closed and toggled, run injection carriage forward until nozzle is seated in the mold bushing.
4. Adjust carriage stop so that carriage will not move forward when clamp is opened.
5. Cycle clamp several times and watch nozzle and injection carriage as machine toggles. Be sure deflection of nozzle and movement of injection carriage is the minimum that maintains a good seal of the nozzle and mold bushing.
6. Readjust carriage stop after machine has been running long enough for the temperatures to stabilize.

IMPINGING RECTANGULAR GATES


SIDE
t
W
OVERLAP
t
W




NON IMPINGING RECTANGULAR GATES
FLASH GATE
t
W
FAN GATE
t
W
GRAMS
50
100
150
200
GATE WIDTH (W)
INCHES
1.0
0.8
0.6
0.4
0.2
24
20
16
12
8
4
MM.
t = 0.04 in.
(1 mm.)
GATE THICKNESS t = 0.08 in.
(2 mm.)
t = 0.12 in.
(3 mm.)
2
4
6
8
WEIGHT OF PART—OUNCES


DIAPHRAGM GATE
GATE
PART
RING GATES
GATE
PART
GATE
PART
FAN GATE
CAVITY
FAN GATE
RUNNER
PARTING LINE
SECTION A-A
FAN GATE
CAVITY
A
A
RUNNER
FLASH GATE
MOLDED PIECE
FLASH GATE
PARALLEL RUNNER
RUNNER
A
A
MOLDED PIECE
FLASH GATE
RUNNER
PARALLEL RUNNER
VIEW A-A

MOLD RECORD CARD NO.

TITLE DWG. NO. PART NO.

MOLD SIZE L. W. H. WT.

KNOCKOUT-MECH. HYD. HYD. / DRAW BAR

KNOCKOUT PATTERN MOLD VENDOR

MOLD TYPE-CONV. HOT RUN INSUL. RUN OTHER

NO. CAVITIES GROSS WT. SHOT

NET WT. / PT. WT. / 100 PARTS

SPRUE & RUNNER WT.

MAT'L. SPECS	PTS. / SHIFT
1.	
2.	
3.	
4.	

NOZZLE RADIUS ORIFICE PENETRATION

Mold and Die Steels

Two Steels for Structural Sections

DESCRIPTION

TYPICAL ANALYSIS

D-M-E NO. 1 STEEL

D-M-E No. 1 steel is a medium carbon (SAE 1030), silicon-killed forging quality steel with approximately 25% greater tensile strength than typical low carbon warehouse steels. It machines easily, but is not "sticky," permitting a faster and smoother cut.

C	0.30%
Mn	0.75%
P	0.04% Max.
S	0.05% Max.
Si	0.25%

D-M-E NO. 2 STEEL

D-M-E No. 2 steel is an AISi 4130 type steel. It is supplied pre-heat treated to 300 Bhn. (269-321). A high strength, free machining steel, D-M-E No. 2 is ideal for holder blocks, clamping plates and support plates in molds and dies.

C	0.30%
Mn	1.20%
P	0.03%
S	0.04%
Si	0.28%
Mo	0.20%
Cr	0.75%

Three Steels for Cavities and Cores

DESCRIPTION

D-M-E NO. 3 STEEL

D-M-E No. 3 steel is a P-20 AISI 4130 (modified) type cavity steel. It is electric furnace melted and vacuum carbon deoxidized. Further refinement is performed by either an electroslag remelt (ESR) or argon calcium treated process, resulting in an exceptionally clean, inclusion-free cavity steel. D-M-E No. 3 steel is pre-heat treated to 300 Bhn. (277-331). It provides high hardness, good machinability and exceptional polishability for both plastics molds and die cast dies.

C	0.30%
Mn	0.85%
P	0.015%
S	0.003%
Si	0.30%
Cr	1.10%
V	0.08%
Mo	0.55%

D-M-E NO. 5 STEEL

D-M-E No. 5 steel is a thermal shock resistant, hotwork die steel (AISI-SAE H-13 type). It is electric furnace melted and vacuum degassed. Supplied fully annealed (approx. 200 Bhn.) for easy machinability, it can be subsequently heat treated to the desired hardness with a minimum of deformation.

Mainly used for die cast dies, it is also suitable for plastics molds with exceptional hardness or polishability requirements.

C	0.40%
Mn	0.40%
Si	1.10%
Mo	1.00%
Cr	5.00%
V	1.10%

D-M-E NO. 6 STEEL

D-M-E No. 6 steel is an electric furnace melted, vacuum degassed T-420 type stainless steel. It is supplied fully annealed to 220 Bhn. (200-240), making it readily machinable.

It can be used for injection, compression or transfer molds where the properties of the plastics materials or excessive condensation require a highly corrosion resistant cavity steel.

C	0.30% to 0.40%
Mn	1.00% Max.
Si	1.00% Max.
Cr	13.00%

Steels for Plastic Molding

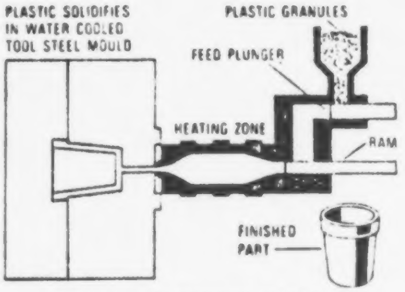
The three standard steels used in plastic molding are shown in the chart at right. Once again they are listed with the most wear resistant steels at the top of the list and the toughest steels at the bottom.

Plastic molding consists of two basic methods (a) injection molding and (b) compression molding. Transfer molding is a modification of compression molding. The two primary methods have one basic difference. In injection molding molten plastic is injected and solidified in the die. Injection molded plastics are generally less abrasive than the ones which are compression molded. For this reason Atlas Mold Special (P20) steel is used for many injection molding dies. For longer runs, more than 10,000 parts, Dievac heat treated to Rc50-52 is the choice.

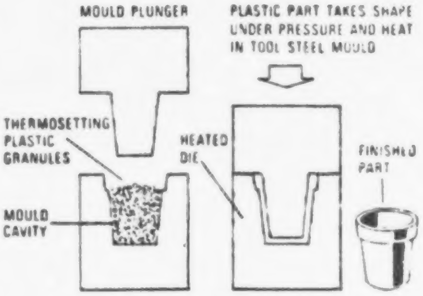
Compression molding, shown in principle in the diagram, consists of feeding solid plastic granules into the die, melting and molding it to shape under temperature and pressure. In the solid form compression molded plastics are much more abrasive than injection molded plastics. For these applications Superimpacto PQ (plastic quality) carburized to a surface hardness of Rc54-56 is an excellent choice. Some plastics, notably the silicones, are molded at temperatures above 600°F (315°C). Such conditions require the use of a hot work tool steel. Dievac (H13) heat treated to Rc50-52 is recommended.

The vinyl plastics are well known for their corrosive attack on die steels. Atlas 420 P.Q. stainless steel heat treated to Rc40-45 gives excellent service under these conditions.

As covered earlier, many plastic dies must be mirror polished. Vacuum arc remelted Dievac heat treated to Rc50-52 should be specified for such applications.



PLASTIC INJECTION MOLDING


MOULD PLUNGER
PLASTIC PART TAKES SHAPE UNDER PRESSURE AND HEAT IN TOOL STEEL MOULD
THERMOSETTING PLASTIC GRANULES
HEATED DIE
FINISHED PART
MOULD CAVITY

PLASTIC COMPRESSION MOLDING

The following table gives the recommended grades and die hardnesses for various plastic molding applications:

RECOMMENDED TOOL STEEL FOR PLASTIC MOLDING

Molding Applications	All Injection Molded Plastics and Short Run* Compression Molded Plastics	All Corrosive Plastics e g Vinyls	Long Run† Compression Molded Plastics	Long Run† Compression Molded Plastics	All Plastics Where Finish Is Critical
Molding Temparature	Up to 400°F (205°C)	Up to 800°F (425°C)	Up to 400°F (205°C)	Over 400°F (205°C)	Over 400°F (205°C)
Steel Recommended	**Mold Special** (P20)	**Stainless** 420-P Q	**Superimpacto PQ** (P6)	**Dievac** (H-13)	**Dievac** (H-13)
Die Hardness	as supplied Rc28-32	heat treated Rc40-45	carburized and air hardened Rc54-56	heat treated Rc50-52	heat treated Rc50-52

* Short Run: Up to 10,000 molded parts

† Long Run: Over 10,000 molded parts

PROPER MOLD STEEL SELECTION AND HEAT TREATMENT

A KEY TO A GOOD MOLD

I. Properties Desired in Plastic Mold Steels

Wear Resistance (High surface hardness)

Good Core Toughness

Adequate Hardenability

Good Size Stability

Polishability

Good Machinability

Hobbability

Weldability

I. Four Classes of Mold Steels

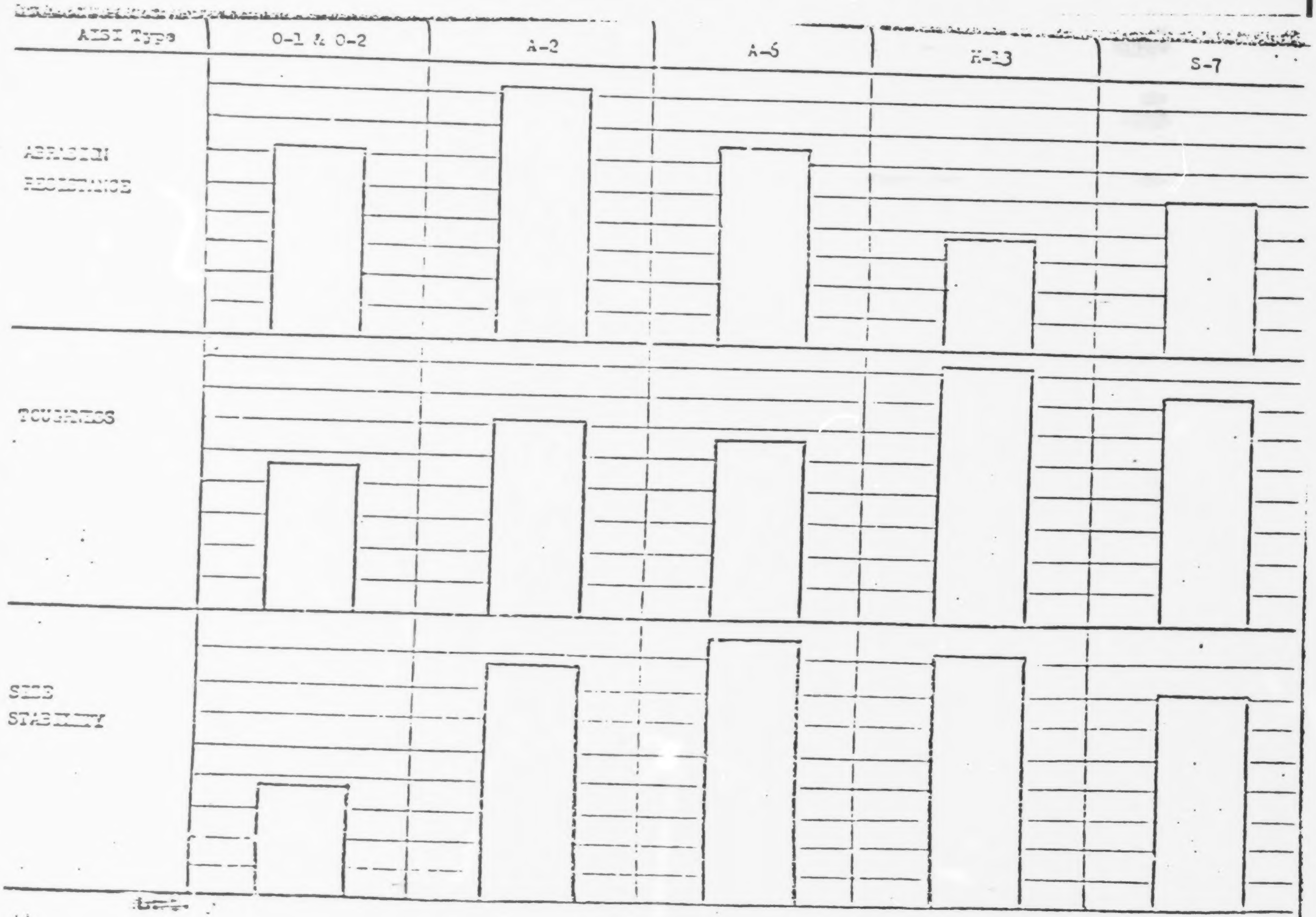
A. Cold hobbing (P-2)

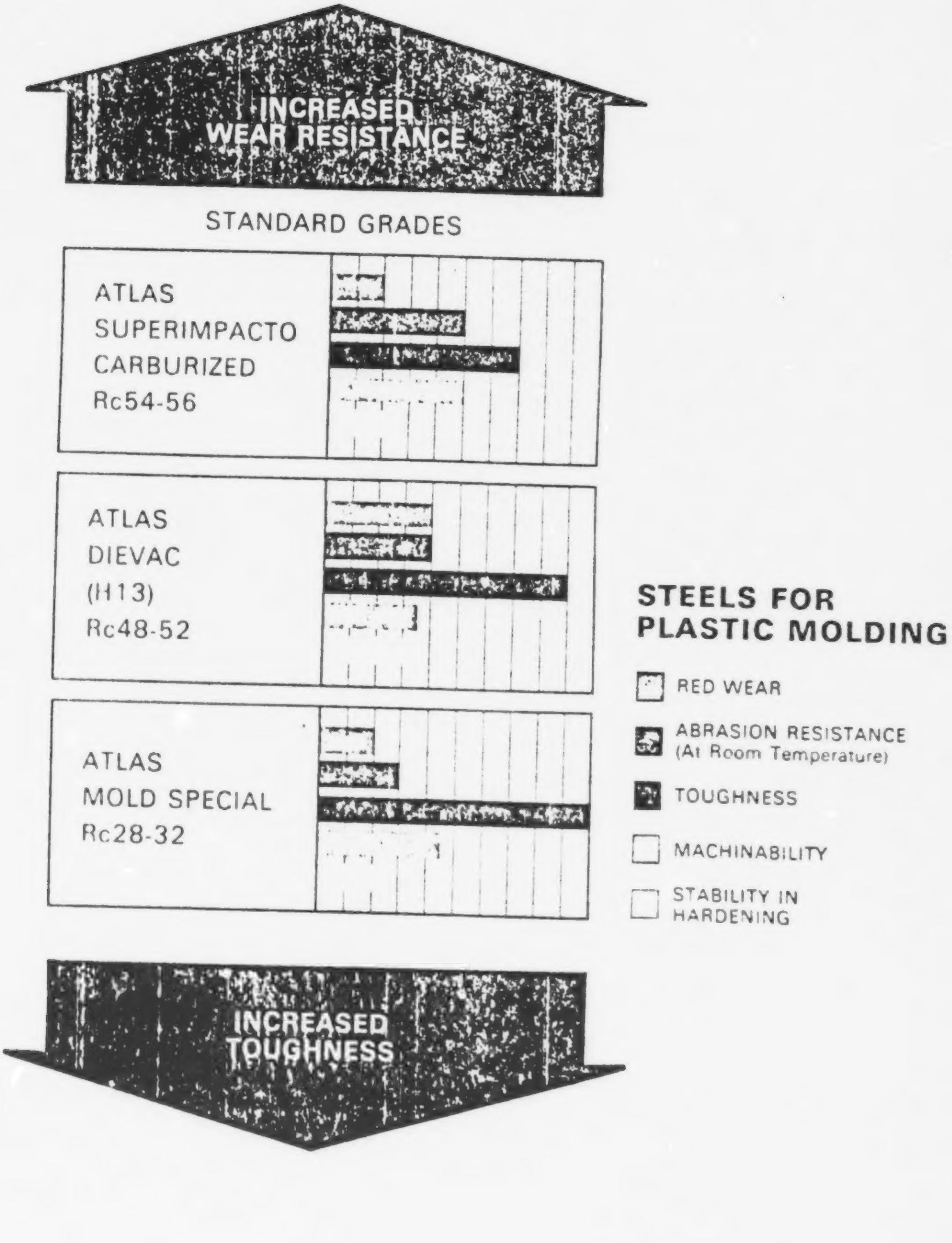
B. Prehardened (P-20)

C. Deep hardening

D. Special purpose mold steels

- Stainless steels (Type 420)
- Maraging steels
- Steels for high abrasion resistance


AISI Type
O-1 & O-2
A-2
A-6
H-13
S-7
ABRASION RESISTANCE
TOUGHNESS
SIZE STABILITY


INCREASED WEAR RESISTANCE
STANDARD GRADES
ATLAS SUPERIMPACTO CARBURIZED Rc54-56
ATLAS DIEVAC (H13) Rc48-52
ATLAS MOLD SPECIAL Rc28-32
INCREASED TOUGHNESS
STEELS FOR PLASTIC MOLDING
RED WEAR
ABRASION RESISTANCE (At Room Temperature)
TOUGHNESS
MACHINABILITY
STABILITY IN HARDENING

Product designer's mold checklist

This first quick review will remind the designer of tasks he should accomplish before a product drawing is sent out for quotation. The second checklist is intended for use by the individual responsible for obtaining a quote on the cost of a molding job, and includes mold and molding considerations that are important to estimating mold costs.

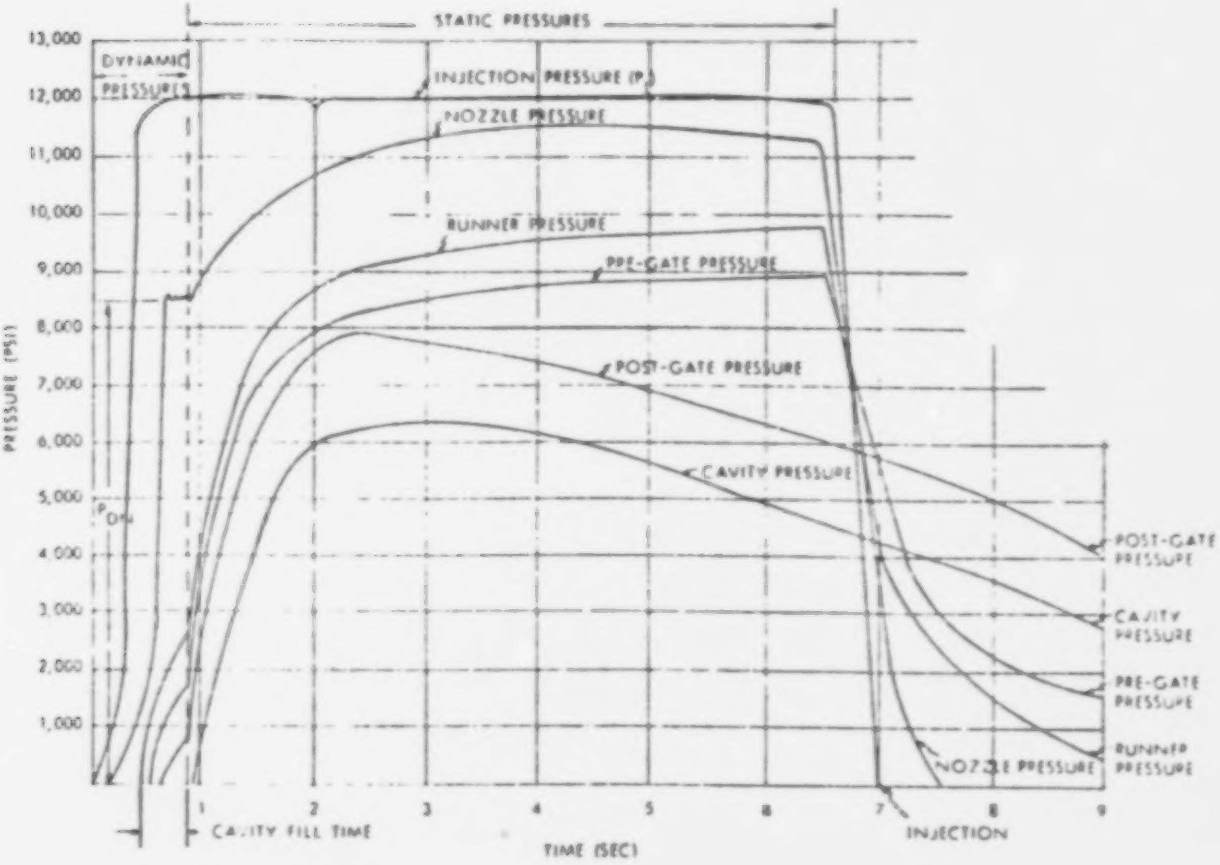
Part I.

☐ 1. Review requirements of end use.
☐ 2. Establish molding material.
☐ 3. Establish molding material shrinkage.
☐ 4. Establish workable tolerances.
☐ 5. Establish parting lines.
☐ 6. Establish acceptable ejection locations.
☐ 7. Establish gating areas.
☐ 8. Establish surface finish required.
☐ 9. Check insert design and source.
☐ 10. Review assembly requirements.

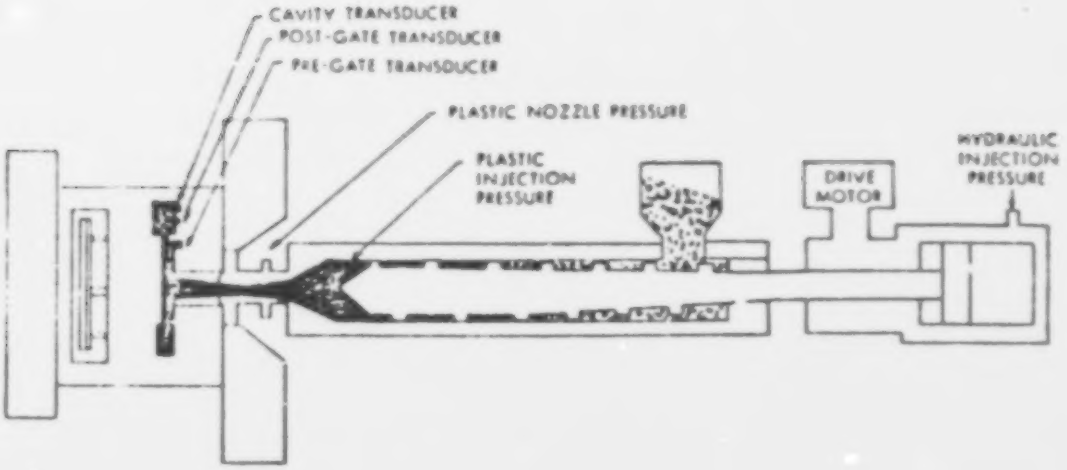
Part II.

☐ 1. Review above specifications with product designer.
☐ 2. Establish number of cavities.
☐ 3. Establish over-all mold size limitations for molding equipment to be used.
☐ 4. Establish sprue, runner and gate sizes.
  ☐ A. Establish runner type, gating system and mechanization for injection mold.
  ☐ B. OR establish land areas, depth of loading well for compression mold.
  ☐ C. OR establish chamber, runner (sprue, if desirable) and gate sizes for transfer molding.
  ☐ D. OR establish land areas, loading board specifications for automatic compression mold.
☐ 5. Establish ejection system.
☐ 6. Establish heating or cooling system.
☐ 7. Establish specific type of mold design.
☐ 8. Establish horizontal or angular coring system.
☐ 9. Review tool drawings.
☐ 10. Review projected areas and material volume capacity to equipment and molding material limitations.
☐ 11. Issue purchase orders.
  ☐ A. Establish mold delivery and advise customer.
  ☐ B. Issue sample order to molding production department.
  ☐ C. Issue special instructions for mold set-up and operation.
  ☐ D. Review with production, tool, quality, set-up and management personnel.
  ☐ E. Plan for fixtures, inserts or special mold installations ahead of scheduled mold delivery.
☐ 12. Follow mold progress at regular intervals of mold construction.
☐ 13. Check mold upon completion at vendor's plant.
  ☐ A. Review shipping instructions to avoid delay if production scheduling requires special attention.
☐ 14. Review mold upon completion of sampling.
☐ 15. Note and communicate areas of difficulty with product designer and mold builder.

TYPICAL PLASTIC PRESSURE PROFILES



LOCATION OF MEASURING INSTRUMENTS


CAVITY TRANSDUCER
POST-GATE TRANSDUCER
PRE-GATE TRANSDUCER
PLASTIC NOZZLE PRESSURE
PLASTIC INJECTION PRESSURE
DRIVE MOTOR
HYDRAULIC INJECTION PRESSURE

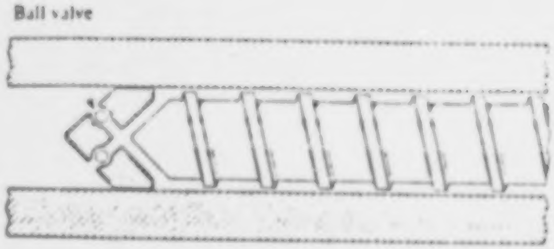
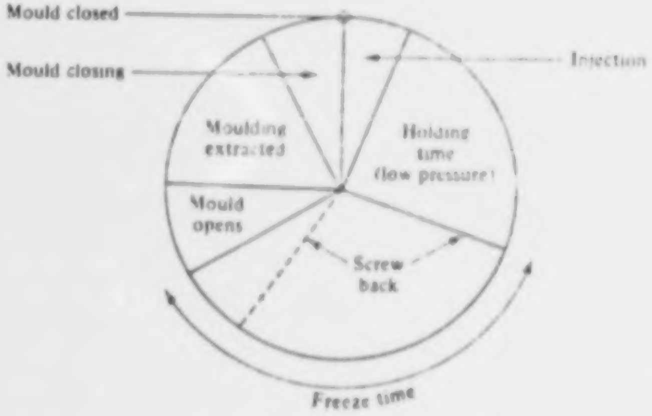


Fig. 2.6h Ball-type non-return valve on nose of screw

by limit switches which act on electrically operated valves to stop screw rotation or to shut off the flow of hydraulic fluid to the cylinder when the injection movement of the screw is complete.

Screw machine operation. A typical sequence of operations from start up is as follows (Fig. 2.7)

(1) Starting with an empty cylinder, granular material from the feed hopper falls on to the rear flights of the screw which rotates, carrying material to the front of the cylinder. During its passage along the cylinder it is plasticized to a fluid state. Some material may escape through the nozzle but the back pressure is generally sufficient to push the screw back in the cylinder and to provide a reservoir of fluid plastic in the front of the cylinder ready for injection.
(2) The mould closes and the cylinder moves forward on its carriage until the nozzle is in contact with the entrance to the mould.
(3) The screw is moved forward by the hydraulic cylinder at the rear of the machine and injection takes place.



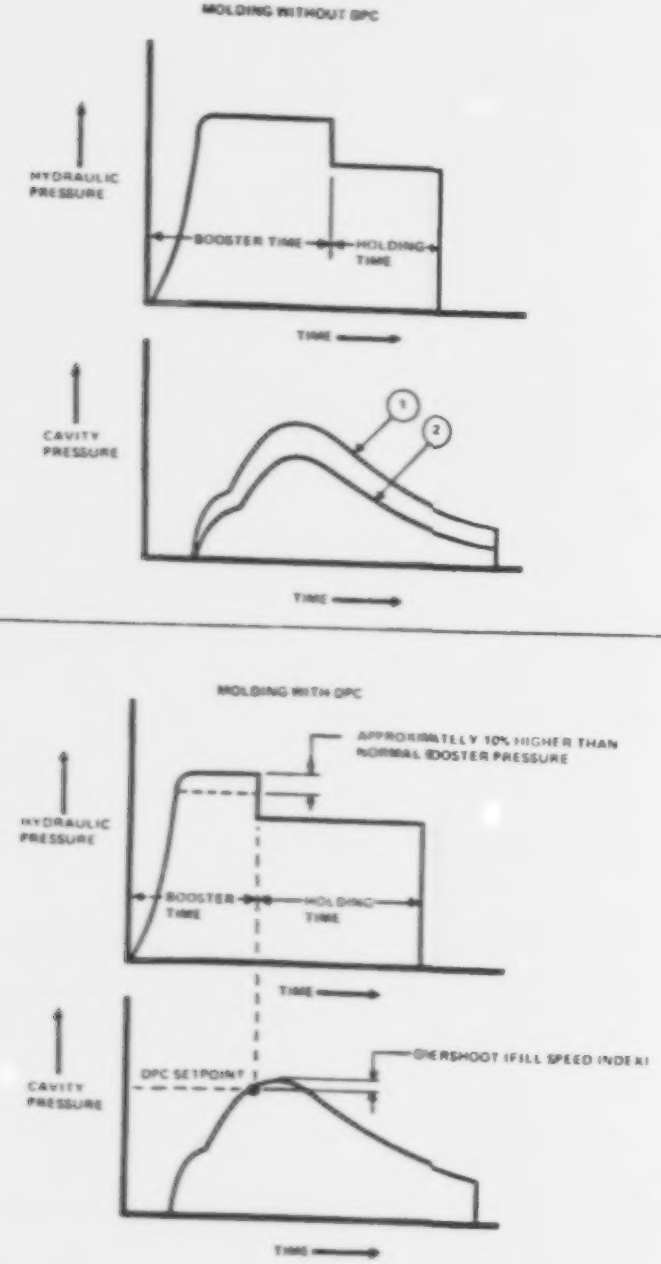
Cycle of operations (screw machine)

(4) After a short interval (the holding time) the screw rotates, creating some pressure in the barrel, which forces it back against low pressure in the hydraulic cylinder, until the limit switch operates, stopping the rotation. This plasticizes material ready for the next shot.
(5) The mould opens, the moulding is ejected, and the mould closes again ready for the next cycle.
(6) Stages (2) to (5) repeat.

Advantages of reciprocating screw machines. There are several advantages to be gained in using the reciprocating screw system. Among these are:

(a) The exact volume of *fluid* material required for filling the mould can be very accurately metered because the limit switches are capable of being adjusted with micrometer precision.
(b) Pressure drop caused by the torpedo is avoided.
(c) It is not necessary to consider weight feeding and the use of complicated self-compensating feed devices is avoided.
(d) The screw is acting as a plunger on a homogeneous melt and the pressure applied to the mould becomes predictable.
(e) Frictional losses in the cylinder are minimal.
(f) Heat transfer in the cylinder is improved because of the mixing action of the rotating screw. This also supplies some mechanical heat because of its shearing action on the viscous plastic.
(g) Because the process is more predictable it is possible to use a smaller locking force for a given area of moulding.
(h) Higher injection speeds are possible.

Figures 2.1 and 2.7 (the cycle of operations) show that the only difference between the cycle for a plunger machine and that for a reciprocating screw machine is the feeding of the new charge to the cylinder. Instead of 'plunger withdrawal', the screw rotates and is displaced backwards along the cylinder, the operation being known as 'screw back'. This takes place during the extension of cooling time (freeze time) but for most efficient operation should not be allowed to extend the freeze time beyond what is actually required for the hardening of the moulding. Most machines are sequenced so that the mould cannot open until screw rotation is complete. This effectively prevents the full cycle operating if the feed hopper becomes empty and also prevents any leakage of material from the nozzle when the mould is opened unless pressure has been developed inside the cylinder during screw back. To obviate any possibility of nozzle leakage because of this, many machines are now fitted with decompression in which, after screw back is complete, the screw is slightly drawn back to relieve the pressure. Decompression—commonly called 'suck back'— should not be excessive or air will be drawn into the hot nozzle where it can cause oxidation of the molten plastic. It is also desirable to keep the screw-back time and the speed of rotation of the screw constant from shot to shot so that the same amount of mechanical heat is supplied to the material at each cycle.


MOLDING WITHOUT DPC
HYDRAULIC PRESSURE
BOOSTER TIME
HOLDING TIME
TIME
CAVITY PRESSURE
1
2
TIME
MOLDING WITH DPC
APPROXIMATELY 10% HIGHER THAN NORMAL BOOSTER PRESSURE
HYDRAULIC PRESSURE
BOOSTER TIME
HOLDING TIME
TIME
OVERSHOOT (FILL SPEED INDEX)
DPC SETPOINT
CAVITY PRESSURE
TIME

Molding with and without boost cutoff (DPC)
(Courtesy D-M-E Company)

D-M-E

3-Stage Closed Loop Mold Pressure Controller CPI-3000

#499
DANGER
HIGH VOLTAGE

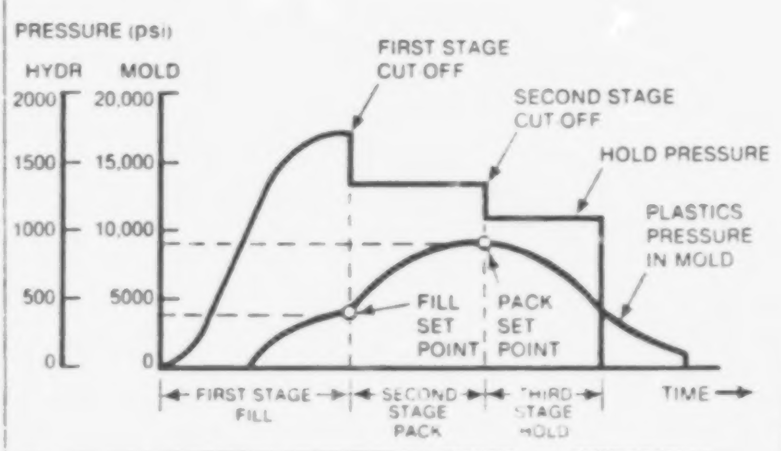
Process is covered under
U S Patent 3 840,312

The CPI-3000 3-Stage Controller is a patented closed loop mold pressure controller designed to automatically correct machine, operator and plastics variations. The system is applicable to large parts with long flowpaths, thin section parts, unbalanced molds, small parts on high-speed molding machines and marginal clamp capacity situations....all of which are susceptible to overpacking, flash and mold damage The CPI-3000 employs a unique 3-stage technique allowing division of the injection cycle into the fill, pack and hold phases. Converting a molding machine to three-stage greatly increases its capability; an added third stage provides the means to separate fill, pack and hold phases, an advantage with or without process control.

This 3-step division of the injection cycle provides the molder with new flexibility For the first time, filling of the mold is totally independent of packing. The molder may now fill a mold rapidly and still pack it to a low pressure. By controlling pack rates independent of pack pressure, molds may also be filled slowly and packed to a high pressure to eliminate flash or burning. Without the CPI-3000, this separation of fill and pack rates would be impossible. A further advantage of 3-stage control is that a controlled amount of "discharge" can be introduced to eliminate warp in thin-walled parts. Discharge can be a very desirable feature under controlled conditions.

Operators find the CPI-3000 easy to use because it clearly and logically controls th fill, pack and hold sequence in molding Each phase of the molding cycle is set achieve the best part characteristics Once set, these conditions are recorded ar may be repeated for subsequent set-ups.

3-STAGE CLOSED LOOP CONTROL



Features	Benefits
3-Stage Injection Control	CPI 3000 connects any machine to patented, 3-stage, automatic, closed loop mold pressure control, providing greater problem solving capability, reduced rejects, easy operator training and increased dimensional accuracy of molded parts
Fill Time And Pack Time Clocks	The digital fill time clock displays the precise time used to fill the mold with plastics while the pack time clock shows the time between the end of fill and the end of pack . . . a measure of actual pack rate Both digital clocks read to 19 99 seconds maximum with .01 seconds resolution
High /Low Alarm Window	High and low alarms are provided to activate an audible visual alarm, reverse a conveyor or shut down the machine whenever existing conditions cannot be maintained (e g during start up or when the hopper is out of material)
Safety Disconnect Circuit	The CPI 3000 is designed to be fail-safe. If it is unplugged from the machine or power, an "abort" circuit will stop injection
Human Engineered Controls	Single meter function switch allows the readout to display all setpoints and data. LED indicators on the front panel clearly show the sequence of the cycle Front panel recorder output allows easy connection of a recorder for hard copy data gathering. Ejector pin size switch allows sensing of actual psi by dialing in the pin size
Operator Training	Using a 3 stage molding machine is much easier than using a 2-stage machine because a mold logically must be filled at a certain speed, packed to a certain pressure, and the pressure held for a certain period of time
Simplified Installation	A standard installation package uses rugged, electro-hydraulic or directional hydraulic valves which any maintenance person can service, repair or replace.

ITEMS TO CONSIDER WHEN SETTING MOLDS

1. Even though some of these things seem elementary, they need to be checked every time.

   A. Does mold fit press in terms of shot size and shut-height? Will the mold fit between the tie bars?

   B. Does locating ring fit platen locator?

   C. Does spherical radius of sprue bushing match nozzle spherical radius?

   D. Can the mold be clamped to the platen with enough clamps?

   E. Are the K.O. bars within 0.005 of each other in length?

   F. Is the K.O. bar of the press set properly so as to prevent overstroke of the ejector bar in the mold?

   G. Are there enough water lines, (in and out) available to attach to the mold?

   H. If the mold needs heated water are temperature circulators available?

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Shrinkage: The hidden troublemaker

The increasing use of plastics in critical and complex designs and the current emphasis on the designer's responsibility for product performance have created the need for a better understanding of this potential problem—and what can be done about it.

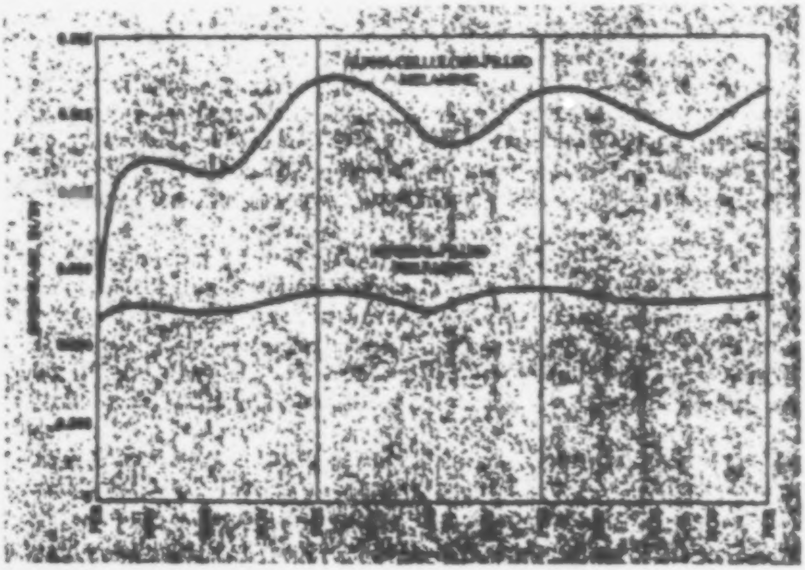


Figure 1. In some plastics, shrinkage may continue beyond the first 48 hours after demolding. The long-term shrinkage rates of two filled melamines reflect seasonal changes of temperature and humidity. (Source: American Cyanamid Co.)

More often than necessary, designers of plastics parts or products experience problems with dimensional changes that occur during or after molding. The cause, in many cases, is an unanticipated material shrinkage.

There are two types of shrinkage. **Mold shrinkage** is defined as the difference between the linear dimension of the mold at room temperature and the corresponding linear dimension of the molded product after 48 hours at room temperature immediately following molding. Experienced mold designers can sometimes—but not always—predict mold shrinkage. Mold shrinkage is not always the same even in identical cavities of a multiple-cavity mold. In many cases, mold-shrinkage adjustments must be made after mold sampling.

Postmold shrinkage refers to the tendency of some materials to continue to shrink beyond the first 48 hours after demolding. Figure 1 illustrates the fluctuations that occur in shrinkage continuing for very long periods in melamine compounds. Note that during dry months the shrink is at maximum, decreasing during months of high humidity.

(continued)

The problem of shrinkage has, of course, been recognized for some time. For example, the postmolding shrinkage of urea/melamine compounds (used in electrical applications for their arc-resistance properties and in other applications for, among other properties, their colorability) is generally known, and material suppliers make available reliable data to help guide the designer.

It is also well known that polyethylene shrinks with time, and that techniques for filling milk bottles, for example, must be adjusted to account for the shrinkage. When the bottles are filled immediately after blowing, no shrink has occurred, but if they are filled even a few days later, the bottles will have shrunk. Because bottles are filled to a fill line, rather than with a specific amount of milk, the buyer is shortchanged by the delayed filling. To compensate for the delay between blowing and filling, a size adjustment must often be included in the mold design. With stock bottles, an annealing operation may be needed to compensate for the postblow shrinkage.

Shrinkage causes many different kinds of design problems. For example, when materials that are known to shrink are used in close proximity to moisture-absorbing or expanding materials, the designer may be in for double trouble. In addition, when two halves of a part made of the same material are stored separately under different environmental conditions, they may not mesh together perfectly when put into service.

Actually, there are a great many shrinkage/expansion situations that can cause problems for the product designer. But at least some of them can be avoided.

PREMOLDING PRECAUTIONS

It is essential that the product designer include all important long term dimensional tolerances on the product drawing. This should be supplemented by notes for the materials engineer, reporting all adverse environmental conditions, such as humidity, radiation, heat cycling and so on, that may cause dimensional change.

The materials engineer — or whoever fills this function — then becomes responsible for selecting a material that will maintain the specified tolerances under the stipulated age and environmental performance conditions. After the material-selection details are added to the drawing, the materials engineer should add to the drawing the essential details concerning the postmolding operations required. Examples would be annealing or the use of shrink fixtures.

The mold-design engineer computes the mold-shrinkage allowance on the basis of information provided by the material supplier and his experience as a mold designer in applying this information. A properly calculated mold shrinkage allowance enables the part to be molded within limits that permit subsequent postmolding annealing or machining operations, thus ensuring delivery of a part that can meet the product-life tolerances specified by the product designer.

For parts that must retain very close dimensions, there is no alternative to cutting the mold cavities undersize and the cores oversize to permit correction by the removal of metal. Samples are then molded of material produced by a recognized and reproducible formulation under exact production conditions of pressure, temperature and time. The samples should undergo the specific postmolding operations in order to demonstrate the amount and location of dimensional adjustments to the mold that will be required.

Dimensional errors in the application and production of plastics must be anticipated by all parties concerned with design and manufacture. Errors are costly, in terms of both product rejects and product-liability damages. Dimensional changes may be anticipated best by prototyping to learn all of the facts about the dimensional drift during the service life of the part.

FACTORS INFLUENCING SHRINKAGE

Factors that ultimately influence shrinkage include the characteristics of the material, the mold design and all parameters of the molding cycle. Shrinkage is significantly affected by mold temperature, injection pressure, the amount of hold time (pressure on a full cavity), the runner cross section and the gate size. Gate locations also influence both mold shrinkage and postmold shrinkage.

In most cases, shrinkage is less in the direction of material flow into the cavity. This is significant where fillers align themselves in the direction of flow.

Many theories have been expounded about annular shrinkage and the shrinkage of a hole in a molded part. The shrinking hole phenomenon can be demonstrated by postbaking an annular quarter inch deep melamine/phenolic ring for 72 hours at 220F. On a 4-inch-diameter ring with a 1½ inch diameter hole, the procedure resulted in an OD shrinkage of 0.0095 inch/inch and an ID shrinkage of 0.0033 inch/inch, a clear indication of why parts may break around inserts in the post molding or afterbake period.

THERMOSET SHRINKAGE

Mineral- or glass-filled thermosets (with the proper annealing, when such is required) offer the best dimensional stability and freedom from environmental shrinkage. In designing products that utilize a thermoset material to encapsulate electronic components, freedom from postmolding shrinkage is essential.

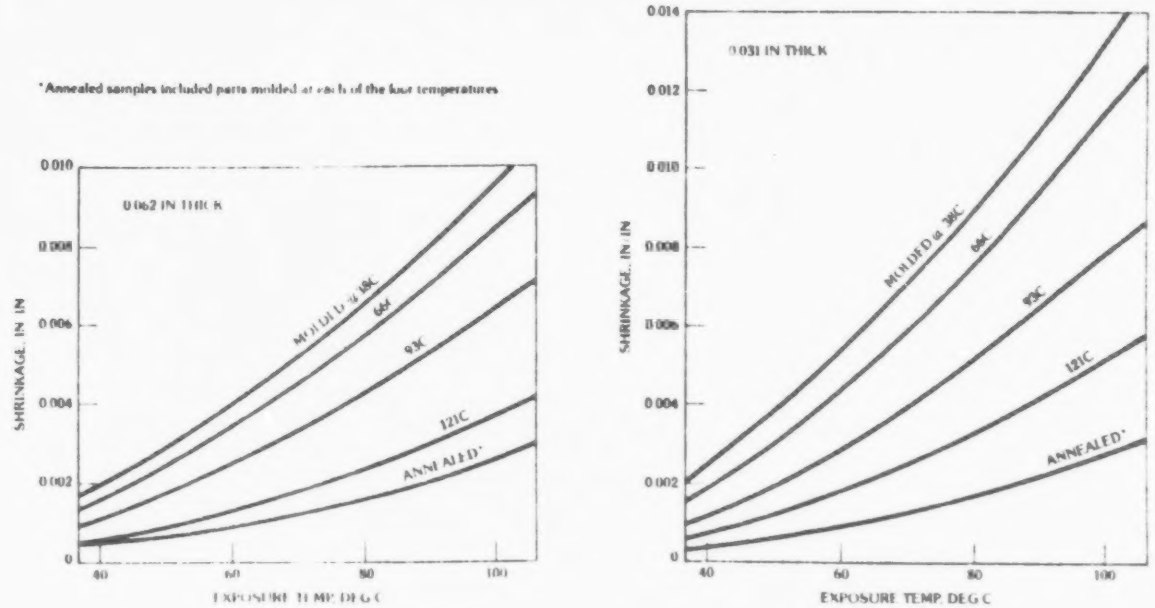
Thermosets have been rated in the order of their dimensional stability as follows:

1. Silicones (most stable)
2. Glass fiber reinforced polyester
3. Diallyl phthalate
4. Alkyds
5. Epoxy
6. Phenolic
7. Urea
8. Melamine

Among the commonly used thermosets, glass fiber-reinforced polyester ranks highest, showing no dimensional change after eight hours at 225 F. Most other thermoset materials show some dimensional change due to afterbake.

An interesting silicone and epoxy compound is the Dow Corning semiconductor grade produced for integrated circuits and other electronic-device encapsulation. The grade is reported to show stability at 70C after 10,000 hours at 93 percent relative humidity. Dimensional change was limited to 0.04 to 0.16 percent after the sample underwent an annealing operation of two hours at 175C and an additional two hours at 200C.

Processing technique has a considerable influence on thermoset shrinkage. Comparison of the shrink measurements



*Annealed samples included parts molded at each of the four temperatures

Figure 2 Postmold shrinkage of 0.062 and 0.031 inch thick homopolymer acetal parts molded at four different temperatures and annealed. Parts were measured at room temperature after 100 hours of exposure time. (Source: DuPont)

of identical thermoset materials with high shrinkage rates has revealed that injection molding brings about the most shrinkage, transfer molding, intermediate shrinkage, and compression molding, minimum shrinkage and uniform directional shrinkage. Thus, the designer should be aware that ASTM D955 values, which are based on compression-molding specimens, have little value for materials to be processed by transfer and injection.

THERMOPLASTIC SHRINKAGE

The postmolding shrinkage of the thermoplastics varies in many cases with the degree of part hardness obtained in the mold before ejection. Highly crystalline plastics may undergo some additional shrinkage over long periods after the piece has cooled to room temperature.

Among the thermoplastics, polypropylene and polyallomers generally exhibit equal shrinkage in the direction of flow and at right angles.

Nylon is a semicrystalline material, with varying proportions of amorphous and crystalline areas, which can result in some unexpected shrinkage differentials. Crystallinity is increased by a slow quench. Slow cooling results in greater shrinkage.

Dimensional stability varies with level of crystallinity. Thick nylon parts are relatively unaffected by cooling temperatures insofar as crystallinity is concerned. All nylons are hygroscopic, and the amount of expansion is proportional to the amount of absorbed moisture. When a crystalline plastics product has undergone its maximum possible shrinkage during processing, it will have its maximum dimensional stability.

Thermoplastic parts with variable wall sections often produce depressed surface areas, or sinks, in which the thicker sections cool more slowly and contract the adjacent surfaces. The dimensional change thus produced may result in poor appearance, nonprintable areas and shortened linear dimensions. Sink problems may be prevented or minimized by wall-section uniformity, by gradual change of section and by careful molding techniques.

Molded acrylic parts increase in dimension during storage because of their moisture absorption. Allowance must be made for this "negative shrinkage" when close assembly fits are planned. For example, if humidity is 40 percent, the designer should allow for an increase in acrylic dimension of 0.001 inch/inch, 65 percent, 0.002 inch/inch; and 80 percent, 0.003 inch/inch.

Accumulated data and experience point to the fact that the many variables limit positive statements and reliable numerical shrinkage values for thermoplastics.

POSTMOLDING SHRINKAGE

The relaxation of residual stresses frozen in the part during the molding process results in contraction or shrinkage of the piece. For example, the postmold shrinkage of acetal copolymer moldings was found to be relatively small, approximately 0.001 to 0.002 inch/inch in the direction of flow. Continuous exposure to high temperatures increased the shrinkage rate, due to more stress relaxation.

Stress relaxation is also greatly affected by the cooling rate after ejection. During slow cooling, thick acetal parts experience more shrinkage than thin parts do. The same parts molded in a hot mold experience less postmold shrinkage. Figure 2 shows the rate of postmold shrinkage of acetal homopolymer.

Postmolding shrinkage can appear even when mold and product design are correct. Insufficient cooling caused by a shortened cycle or an overly high mold temperature can cause some unexpected postmolding shrinkage. When high mold temperatures are not followed by sufficient cooling, the mold pins, which make cored holes in the part, will pull free from the warm part and the postmolding shrinkage will reduce the hole and part size. Mold temperatures must be carefully monitored to minimize postmold shrinkage in thermoplastics.

Guidance must be solicited from the materials suppliers when minimal postmolding shrinkage is essential, and their recommendations must be tested by prototyping and experimentation.

POSTMOLDING TREATMENTS

The injection process for thermoplastics sets up a system of surface and internal stresses in the molded part. The annealing redistributes both surface and internal stresses more uniformly and reduces their magnitude. Annealing cannot completely eliminate the molded-in stresses, but it offers the best guarantee of optimum quality, dimensional stability and useful service life for a product that will be exposed to many in-use and environmental stresses.

The annealing of thermoplastics is a process in which the molded part is heated to a temperature near but below its softening point (or below its melting point in the case of crystalline plastics) and then subjected to slow uniform cooling to bring about stress relaxation without shape distortion. The process may take place in an oil bath or an oven.

Thermoplastic parts may be annealed in an oil bath, provided no reaction takes place between the plastics and the oil. Most refined or nonacidic oils are suitable. When annealing of thermoplastics is done in ovens, the ovens should be the air circulating type capable of holding interior temperatures within 5 deg F.

Many types of ovens are used for annealing thermosets. They must be afterbaked at a temperature that will not reduce their flexural strength, and a flow of air is essential. (Afterbaking or annealing is also called stoving, and stoving time is time in the oven at higher than ambient temperatures.)

Annealing thermosets reduces volatiles, stabilizes dimensions within material limits and elevates thermal endurance.

Postmolding shrinkage often causes inserts that were molded flush to become "proud," as shown in Figure 3. The postmolding assembly of inserts should follow necessary annealing operations.

Figure 4 points up the in-service shrink problems with outside inserts. A special formulation rubber coating applied to inserts to be molded in thermosets often prevents cracking.

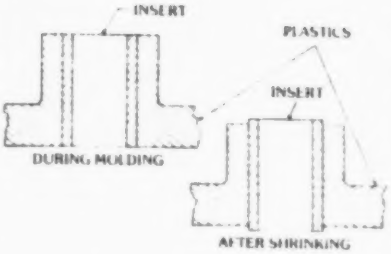


Figure 3. Postmold shrinkage causes plastics with high shrinkage values to shrink below metal inserts, leaving the insert ends protruding above the surface of the part.

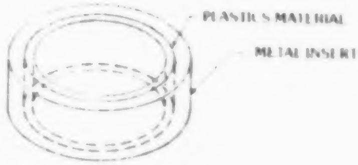


Figure 4. Some plastics, when molded inside metal, shrink away from the metal outsert surface.

While annealing is often omitted, this is an important consideration for the product designer and is a must when parts may be machined, painted, cemented, decorated or exposed to severe stress.

PROCESSING VARIABLES

For the designer who desires a closer look at how processing variables affect shrinkage, one intensive study may be of particular interest. Ing W Woebcken, of Suddeutsches Kunststoffzentrum, Wurzburg, West Germany, has studied the processing variables that affect the dimensional accuracy of injection-molded acetal, 35 percent glass-fiber-reinforced nylon and ABS.

Woebcken has concluded: "The numerous results obtained from the extensive test program for empirically determining shrinkage caused by shape and processing technique have confirmed that it appears impossible, or not yet possible, to make an exact precalculation of process shrinkage and postshrinkage. There are certainly clear pointers, but the relationships are extremely complex."

Woebcken divides the influencing factors into two categories: shape of part and processing conditions. Among the former are five variables:

Length of flow paths. Shrinkage increases as distance from the gate increases, due to the pressure drop in the mold cavity, or the reduction of pressure penetration.

Wall thickness. In general, for the same mold cavity pressure, shrinkage decreases as wall thickness increases due to the increase of pressure penetration.

Local variations in wall thickness. In the rib area, holding pressure has greater effect, thus, there is greater filling and a reduction in shrinkage, resulting in warping in semicrystalline thermoplastics.

Orientation. Longitudinal orientation of molecules and crystallites in the outer wall of an injection-molded part causes greater shrinkage in the injection direction than at right angles to it. This effect is reduced partly by shrinkage of transversely oriented molecules in the center of the molding. However, transverse orientation has no great effect because of stress relaxation. The orientation of such additives as glass fiber causes anisotropic shrinkage; hence, mold shrinkage is less in the injection direction than at right angles to it.

Peripheral effects. Because there is early and more intensive cooling at the outer edge of the mold, shrinkage is less along this edge of the molded part. The effect can be magnified by orienting glass fibers parallel to the edge.

In the category of processing conditions, six variables should be considered:

Temperature of molding compound. Variations in melt temperature within the normal temperature range have little effect (particularly with amorphous thermoplastics, such as ABS), providing all other parameters are kept constant or adjusted. A raised melt temperature could indirectly affect mold shrinkage, for example, by changing the mold-cavity pressure.

Temperature of the mold. Mold temperature greatly influences mold shrinkage and postmolding shrinkage. High temperatures increase mold shrinkage and reduce postmolding shrinkage.

Injection time. Orientation and crystallization are the main factors influenced by injection time.

Holding time. Extended holding pressure time causes a greater degree of filling and thus less mold shrinkage, unless the holding time is less than sealing time (the time it takes the material to harden in the gate and stop the flow into the mold).

Mold-cavity pressure. Mold cavity pressure is affected both by holding pressure in the cylinder head and the pressure drop at the gate. Packing the mold reduces mold shrinkage. In the case of nylon 6, however, the increased degree of filling mainly brings about an increase in weight and wall thickness rather than affecting shrinkage.

Gate type and position. Choice of type and position of gate has a great effect upon shrinkage and dimensional stability owing to its effect on orientation.

Figure 5 summarizes Woebcken's findings with regard to mold cavity pressure and gating variables.

Although no designer can predict all the possible effects of the two types of shrinkage, parts that require substantial dimensional stability for performance may fail if the problem is not anticipated. The important factor is to know what shrinkage can do to a part, whether it will or will not affect long term performance and how it may be accounted for. Factors that minimize shrinkage are (1) careful material selection (the addition of filler and reinforcements substantially decreases shrinkage); (2) attention to gating and design details that influence molecular orientation in the molded part; (3) understanding of the processing effects; and (4) precise prototyping and testing of the actual part to allow the molder and moldmaker to compensate for the shrinkage factor. PDF

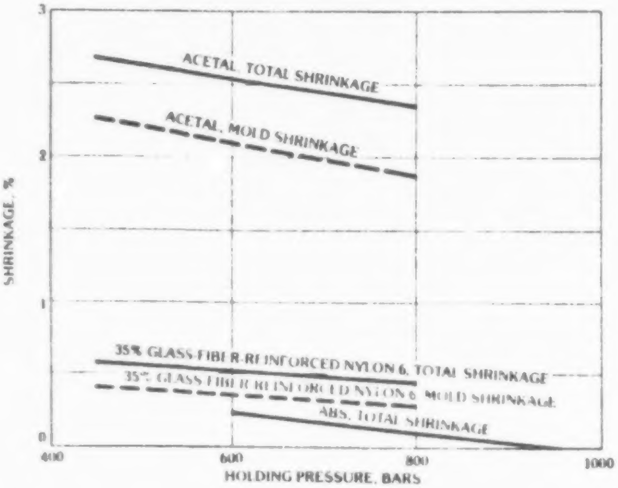


Figure 5. Mold shrinkage and total shrinkage (mold plus postmold shrinkage) of 2-mm-thick acetal and nylon 6 samples and total shrinkage of 2 mm thick ABS samples processed with a sprue gated molding technique. To determine postshrinkage, the samples were kept at 120C for three hours. (Source: March 1977 Industrial & Production Engineering*)*

MOLD RUN CARD NO.

MOLD NO PART NO DWG. NO

PRESS NO.				
PRESS SIZE				
NOZZLE TYPE & DIA				
TIMER SETTING				
DIE CLOSE				
PLUNGER IN				
DELAY UNLOAD (BOOST)				
DIE OPEN				
TOTAL CYCLE TIME				
PRESSURE				
CLAMP				
INJECTION- 1st. STAGE				
-2nd STAGE				
CYLINDER TEMP.				
NOZZLE				
FRONT				
MIDDLE				
REAR				
FEED HOUSING				
MOLD TEMPERATURE (PYROMETER)				
FRONT (COVER)				
BACK (EJECTOR)				
MIDDLE PLATE				
COLD WATER ☐	STERLCO ☐	REFRIG. ☐	OTHER ☐	
PARTS / SHIFT				
SCREW R.P.M.				
BACK PRESSURE				

CELANESE NYLON 6/6

FIGURE 31
Trouble shooting guide for nylon molding problems

PROBLEM	SUGGESTED CORRECTIVE ACTION
SHORT SHOTS	1. Increase Feed 2. Increase Injection Pressure 3. Use Booster and Maximum Ram Speed 4. Decrease Cushion 5. Raise Material Temperature by: a. Raising Cylinder Temperature b. Increasing Screw Speed (Screw Machine) c. Raising Back Pressure (Screw Machine) 6. Raise Mold Temperature 7. Increase Overall Cycle 8. Use Lubricated Material (Plunger Machine) 9. Increase Size of Sprue and/or Runners and/or Gates
FLASHING	1. Lower Material Temperature by: a. Lowering Cylinder Temperature b. Decreasing Screw Speed (Screw Machine) c. Lowering Back Pressure (Screw Machine) 2. Decrease Injection Pressure 3. Decrease Overall Cycle 4. Decrease Plunger Forward Time 5. Check Mold Closure (Possible Obstruction on Parting Line Surface) 6. Improve Mold Venting 7. Check Press Platens for Parallelism 8. Move Mold to Larger (Clamp) Press
NOZZLE DROOL	1. Lower Nozzle Temperature 2. Lower Material Temperature by: a. Lowering Cylinder Temperature b. Decreasing Screw Speed (Screw Machine) c. Lowering Back Pressure (Screw Machine) 3. Decrease Residual Pressure in Cylinder by: a. Reducing Plunger Forward Time b. Increasing "Decompress" Time (If Press Has This Control) 4. Decrease Overall Cycle Time 5. Use Lubricated Material 6. Dry Material 7. Use Nozzle with Smaller Orifice 8. Use Reverse-Taper Nozzle or Nozzle Valve
NOZZLE FREEZE-OFF	1. Raise Nozzle Temperature 2. Decrease Cycle Time 3. Increase Injection Pressure 4. Raise Mold Temperature 5. Use Nozzle with Larger Orifice 6. Use Reverse-Taper Nozzle
DISCOLORATION	1. Purge Heating Cylinder 2. Lower Material Temperature by: a. Lowering Cylinder Temperature b. Decreasing Screw Speed (Screw Machine) c. Lowering Back Pressure (Screw Machine) 3. Lower Nozzle Temperature 4. Shorten Overall Cycle 5. Check Hopper and Feed Zone for Contaminants 6. Check Cylinder and Plunger Fit for Excessive Clearance 7. Check for Proper Cooling of Ram and Feed Zone 8. Provide Additional Vents in Mold 9. Move Mold to Smaller Shot Size Press

FIGURE 31 (cont.)

PROBLEM	SUGGESTED CORRECTIVE ACTION (Cont.)
BURN MARKS	1. Decrease Plunger Speed 2. Decrease Booster Time 3. Decrease Injection Pressure 4. Improve Venting in Mold Cavity 5. Alter Position and/or Increase Gate Size
SPLAY MARKS, SILVER STREAKS, SPLASH MARKS	1. Lower Material Temperature by: a. Lowering Cylinder Temperature b. Decreasing Screw Speed (Screw Machine) c. Lowering Back Pressure (Screw Machine) 2. Lower Nozzle Temperature 3. Shorten Overall Cycle 4. Dry Material Before Use 5. Check for Contamination (e.g., Water or Oil Leaking Into Mold Cavity) 6. Move Mold to Smaller (Shot Size) Press
STICKING IN CAVITIES	1. Decrease Injection Pressure 2. Decrease Plunger Forward Time 3. Decrease Booster Time 4. Adjust Feed for Constant Cushion 5. Increase Mold Closed Time 6. Lower Mold Temperature 7. Decrease Cylinder and Nozzle Temperature 8. Check Mold for Undercuts and/or Insufficient Draft.
STICKING IN SPRUE BUSHING	1. Decrease Injection Pressure 2. Decrease Plunger Forward Time 3. Decrease Booster Time 4. Increase Die Closed Time 5. Increase Mold Temperature at Sprue Bushing 6. Raise Nozzle Temperature 7. Check Sizes and Alignment of Holes in Nozzle and Sprue Bushing (Hole in Sprue Bushing Must Be Larger) 8. Provide More Effective Sprue Puller
WELD LINES	1. Increase Injection Pressure 2. Increase Injection Forward Time 3. Raise Mold Temperature 4. Raise Material Temperature 5. Vent the Cavity in the Weld Area 6. Provide an Overflow Well Adjacent to the Weld Area 7. Change Gate Location to Alter Flow Pattern
SINKS AND/OR VOIDS	1. Increase Injection Pressure 2. Increase Injection Forward Time 3. Use Booster and Maximum Ram Speed 4. Raise Mold Temperature (Voids) 5. Lower Mold Temperature (Sinks) 6. Use Lubricated Material (Plunger Machine) 7. Decrease Cushion 8. Increase Size of Sprue and/or Runners and/or Gates 9. Relocate Gates Nearer Heavy Sections

FIGURE 31 (cont.)

PROBLEM	SUGGESTED CORRECTIVE ACTION (Cont.)
WARPAGE, PART DISTORTION	1. Equalize Temperature in Both Halves of Mold 2. Observe Mold for Uniformity of Part Ejection 3. Check Handling of Parts After Ejection from Mold 4. Increase Plunger Forward Time 5. Try Increased Pressure and Reduced Pressure 6. Try Higher and Lower Mold Temperature 7. Increase Die Closed Time 8. Lower Material Temperature 9. Set Differential Mold Temperatures to Counteract Warp Due to Part Geometry 10. Jig the Part and Cool Uniformity
BRITTLENESS	1. Lower Material Temperature by: a. Lowering Cylinder Temperature b. Decreasing Screw Speed (Screw Machine) c. Lowering Back Pressure 2. Lower Mold Temperature 3. Check for Contamination 4. Increase Injection Speed 5. Decrease Amount of Regrind in Feed 6. Dry Material Before Use 7. Immerse Parts in Water After Molding
DELAMINATION	1. Raise Temperature of Mold and/or Material 2. Eliminate Contamination 3. Dry Material 4. Increase Injection Speed
POOR DIMENSIONAL CONTROL	1. Set Uniform Cycle Times 2. Maintain Uniform Feed and Cushion from Cycle to Cycle 3. Fill Mold as Rapidly as Possible 4. Check Machine Hydraulic and Electrical Systems for Erratic Performance 5. Increase Gate Size 6. Balance Cavities for Uniform Flow 7. Reduce Number of Cavities

10. Cost Estimating of Plastic Parts For Product Designers

When designing a plastic molded component, it is frequently desirable to compute an approximate cost in order to determine whether the considered design is within desired economical limits. The usual practice is to contact a molder, obtain a rough estimate, and proceed on the basis of this information to either redesign or finish the design on hand. This is time consuming, and on many occasions even this step is neglected because of the loss of time involved.

It is the intention of this chapter to provide the designer with the necessary guidelines that will enable him or her to approximate the cost factors to a degree that will point in the proper direction. The following is a simplified version of costing plastics. It covers the main and significant factors that include 85–90% of product value and should suffice for the requirements of a product designer when various designs are comparatively evaluated.

There are two basic ingredients that determine the value of a plastic part:

1. *The cost of the plastic resin (material)*
2. *The cost of molding*

The cost of the plastic material content is derived by calculating the cubic inches of the part and multiplying it by cost per cubic inch as shown in Fig. 5–1.

Once the cubic inches of the part are established, we will utilize these data as the basis for obtaining the remainder of the information, i.e., the cost of molding.

The following steps will lead to the molding cost:

(a) *The thickest portion* of part will determine the molding time required. Figure 10–1 shows how many pieces per hour can be molded of a part of a certain thickness in a single cavity. With a contemplated *yearly activity* and an ordering frequency of say every 45 days, we can tentatively decide on the *number of cavities* needed. The *number of cavities* should be such that it would ke the 45-day requirement to produce in two hundred hours, or

$$\text{Number of cavities} = \frac{\text{45-day requirement}}{\text{200 hr} \times \text{pieces/hr}}$$

(b) *The number of cavities times the cubic inches per cavity* (or piece) leads us to the *machine size* by referring to Table 10–1.

There are a great number of cases in which the volume of material for all the cavities is small and the *projected areas* of the cavities are large; in that event, the choice of machine size is governed by the tonnage of the clamp required to keep the mold from opening during the injection of the material. The required tonnage is obtained by multiplying the *projected areas* of the cavities (parts) by

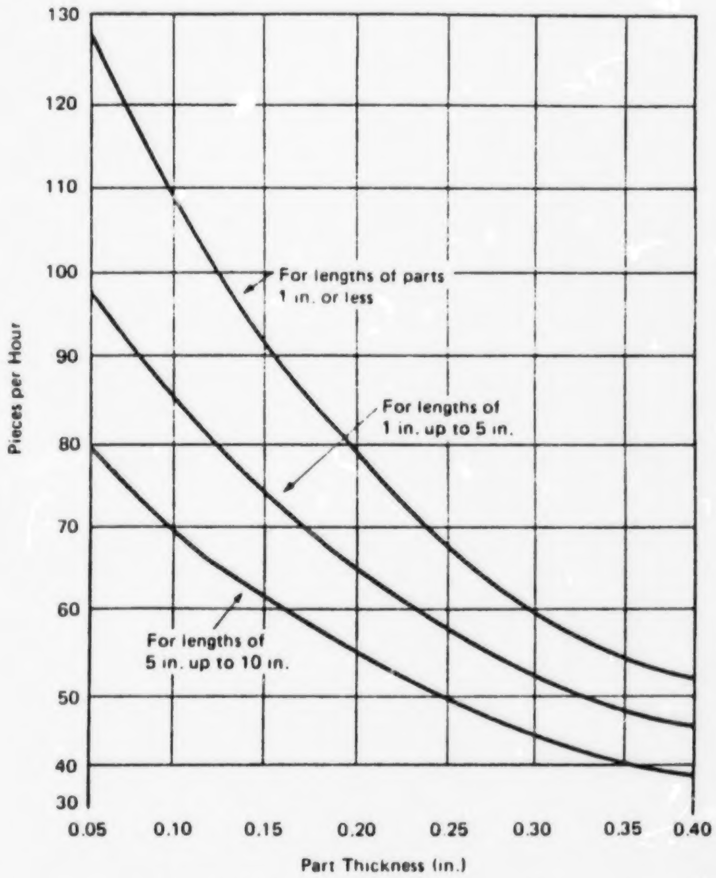


Fig. 10–1. Production per hour vs part thickness.

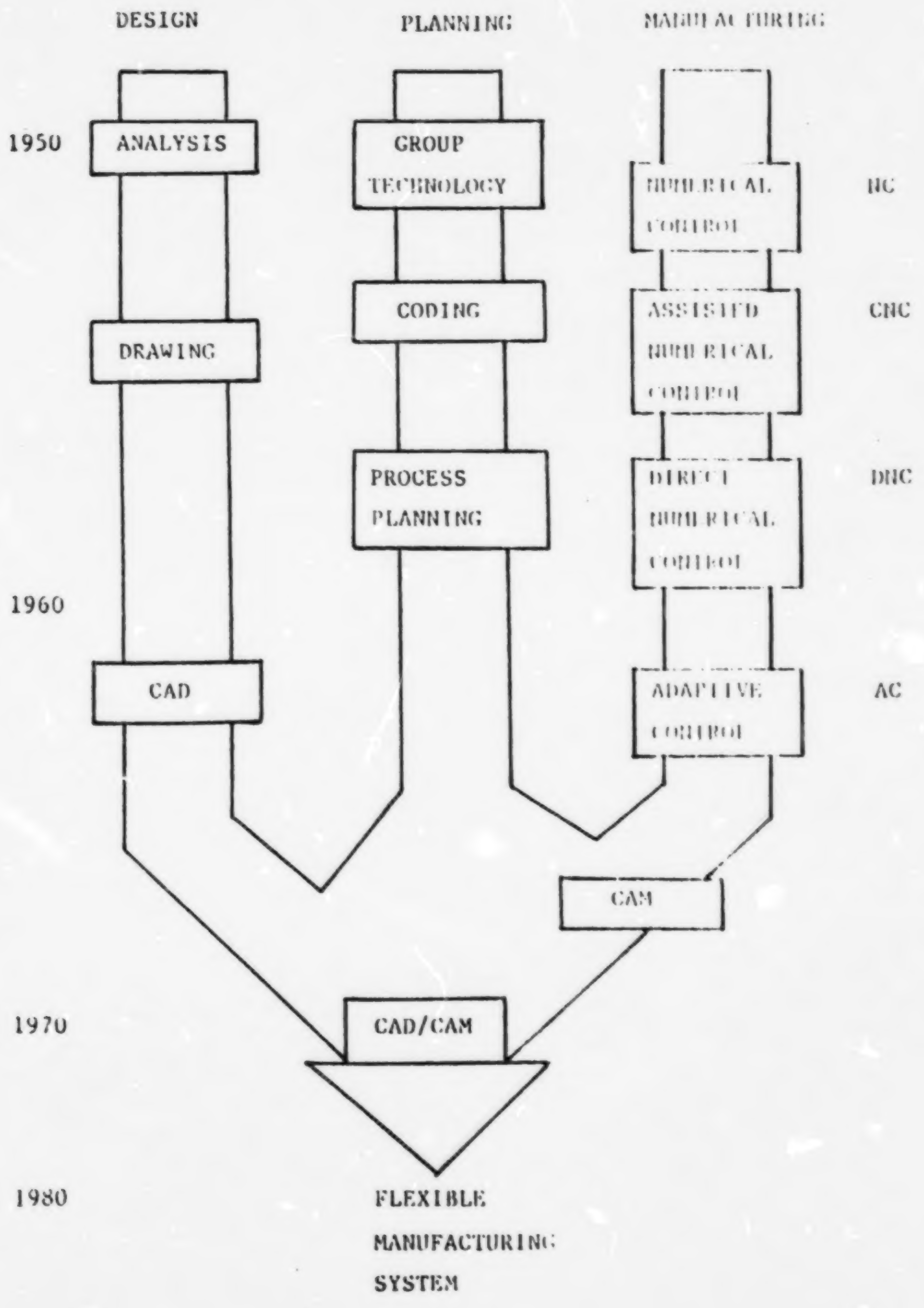
TABLE 10–1

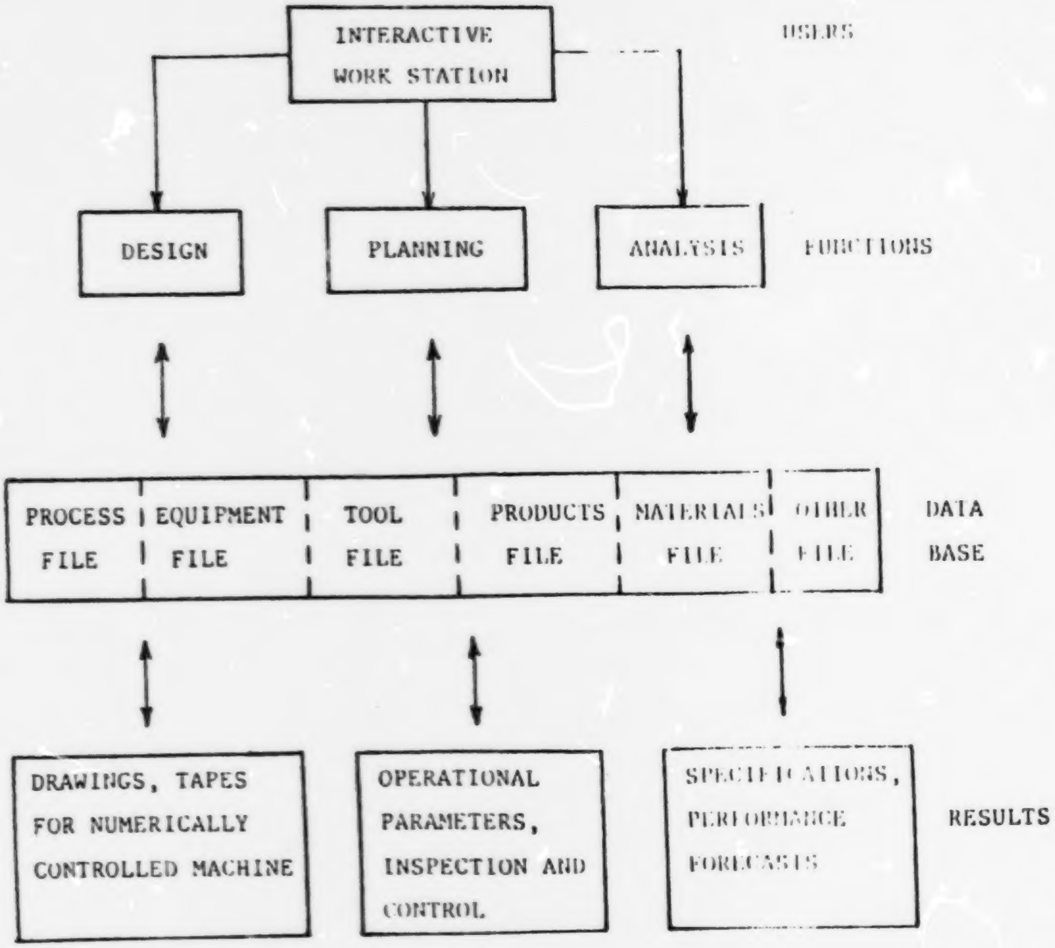
Tons	50	75	100	125	150	200	250	300	350
Cubic inches	4.95	9.9	13.0	16.3	19.8	22.8	32.5	39.0	52.0
Cost per hour ($)	18	23	25	28	30	32	34	37	40

Tons	400	450	500	600	700	800	900	1000
Cubic inches	58.5	65.0	97.5	113.8	156.0	178.0	195.0	208
Cost per hour ($)	43	46	49	54	58	65	72	80

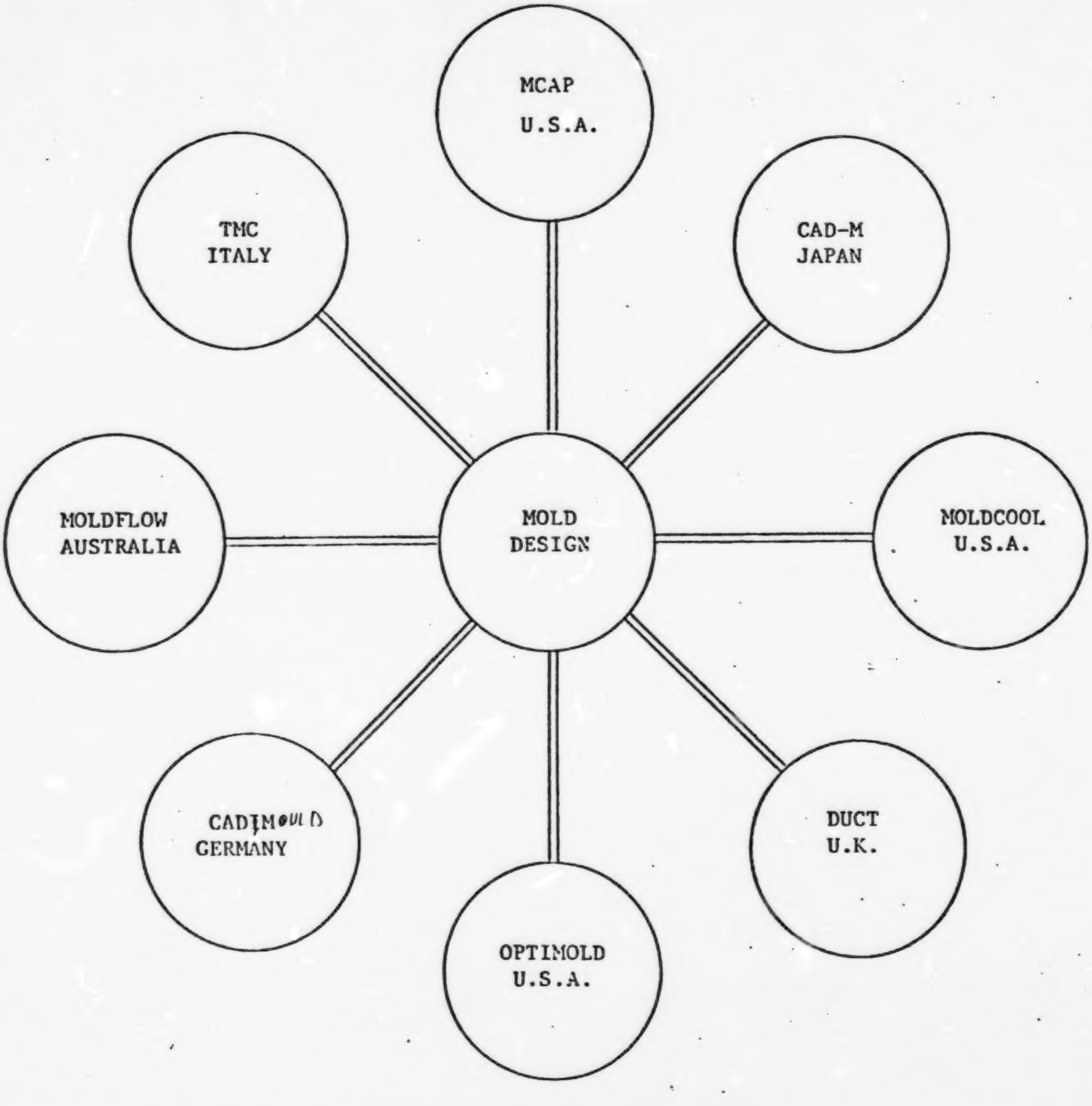
VI-1

HISTORIC EVOLUTION OF CAD/CAM

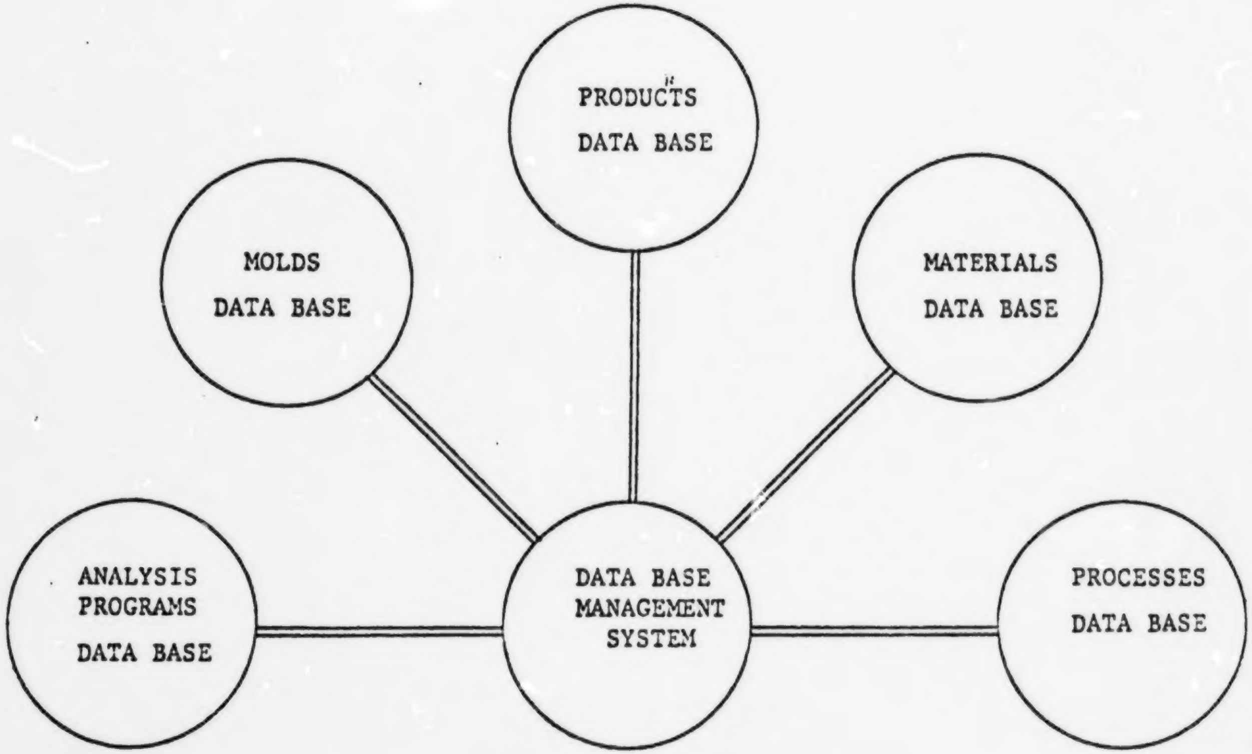

DESIGN
PLANNING
MANUFACTURING
1950
ANALYSIS
GROUP TECHNOLOGY
NUMERICAL CONTROL
NC
CODING
ASSISTED NUMERICAL CONTROL
CNC
DRAWING
PROCESS PLANNING
DIRECT NUMERICAL CONTROL
DNC
1960
CAD
ADAPTIVE CONTROL
AC
CAM
1970
CAD/CAM
1980
FLEXIBLE MANUFACTURING SYSTEM


INTERACTIVE WORK STATION
USERS
DESIGN
PLANNING
ANALYSIS
FUNCTIONS
PROCESS FILE
EQUIPMENT FILE
TOOL FILE
PRODUCTS FILE
MATERIALS FILE
OTHER FILE
DATA BASE
DRAWINGS, TAPES FOR NUMERICALLY CONTROLLED MACHINE
OPERATIONAL PARAMETERS, INSPECTION AND CONTROL
SPECIFICATIONS, PERFORMANCE FORECASTS
RESULTS

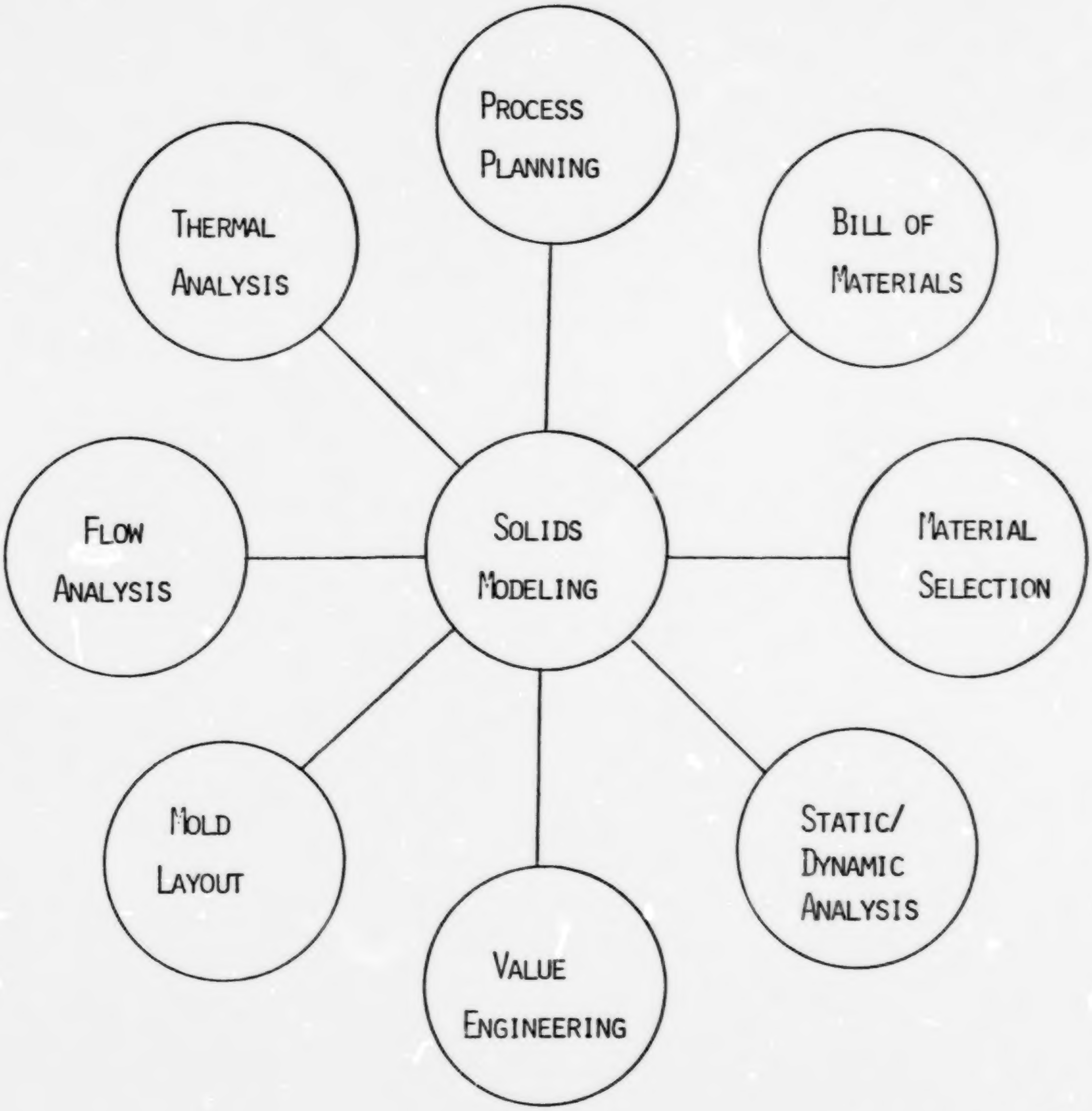
THE CAD/CAM CONCEPT


MCAP
U.S.A.
TMC
ITALY
CAD-M
JAPAN
MOLDFLOW
AUSTRALIA
MOLD
DESIGN
MOLDCOOL
U.S.A.
CADMOULD
GERMANY
DUCT
U.K.
OPTIMOLD
U.S.A.

Worldwide computer-aided mold design systems.


PRODUCTS
DATA BASE
MOLDS
DATA BASE
MATERIALS
DATA BASE
ANALYSIS
PROGRAMS
DATA BASE
DATA BASE
MANAGEMENT
SYSTEM
PROCESSES
DATA BASE

An integrated computer-aided engineering approach for designing injection molds.


PROCESS PLANNING
THERMAL ANALYSIS
BILL OF MATERIALS
FLOW ANALYSIS
SOLIDS MODELING
MATERIAL SELECTION
MOLD LAYOUT
STATIC/ DYNAMIC ANALYSIS
VALUE ENGINEERING

COMPUTER INTEGRATED PRODUCT DEVELOPMENT PROCESS the process.

Once the gate positions have been fixed and the molding conditions have been established, the flow rate, melt temperature, and required pressure in the runner system are determined. If a hot-runner system is to be used, the design of the cavity and a possible cold-runner section is completed first, which then provides the specification—flow rate, melt temperature, and required pressure drop for the hot-runner system.

What the programs predict

The series of computer programs predict pressures, temperatures, shear rates, shear stresses, cooling times, filling patterns, and any other required parameters. The cavity dimensions are described to the computer by means of a mold file. The appropriate material data is taken from a large data base of different plastic materials. Molding conditions are optimized for that mold geometry and material to give the best-possible molding conditions for that particular mold/material combination, including minimizing internal stresses *(Fig. 3)*.

Types of computer services

Services available from a company such as Moldflow Australia range from the supply of a completely integrated computer-graphics system to project design consultation. (Moldflow Australia has computer centers around the world that mold designers can consult on a walk-in basis for design and flow analysis.) Facilities include use of computer-terminal and graphics equipment. Software is available on a time-sharing basis and courses on how to use the programs are available. These can be run on an in-house terminal.

Such services include software as either separate programs or as a full set. At the basic level, this allows the graphic system to generate all input data necessary to describe the mold geometry, and write this information onto a series of files. These files are then transferred to the time-sharing system, where finite element analysis is done. Result files are then brought back onto the local system. The graphics system then displays the full flow pattern graphically as a part, usually shown as an isometric *(Fig. 4)*.

At a higher level, a full library of programs can be supplied to run with the graphics system. The whole analysis is done on the local system without using time-sharing.

Alternately, a complete package, including the graphic programs can be installed on an in-house computer system. Training in the concepts of plastics flow and in the application of computer programs is available.

Computerized machining

Moldmakers are turning to automation for extra precision, efficiency and, frequently, as a partial remedy for the skilled-labor shortage. Among front-running technologies, electric-discharge machining (EDM) and computer-based numerical controls (CNCs) are advantageously combined—at least for ultradifficult jobs.

When it comes to producing complex shapes (such as molds for plastic parts), electrical discharge machining (EDM) is often the only practical way to do the job. Yet it is not usually available even when the need exists. It's surprising, because EDM is not new; it dates back some 30 years, when conventional machine tools first gave way to the "spark erosion" concept for cutting metal. The process has been gradual in catching on, however, inching ahead, as the new technology proved its value; and it has a way to go. During the same period of time, the explosion in electronics spawned sophisticated numerical controls (NCs) of all types at gradually diminishing costs. They have become standard in most modern machine shops. Today, numerical controls are computer-based (CNCs) and attracting attention in EDM centers. The combination represents a giant-step forward in metal cutting.

How EDM works

Essentially electrical discharge machining makes use of a metal-eroding electric spark emitted between a pair of electrodes. The spark, rather than a metal tool, does the cutting. The electrodes are the workpiece itself and a carbon (or copper) electrode. A few simple electrodes contoured to handle the reverse shape of part segments can erode complex workpieces such as multicavity molds. (See *Fig. 5*.) In operation, both are immersed in a circulating solution that cools the workpiece and flushes away the eroding material. Shaping is done in stages. The workpiece is first brought to an approximate shape by a series of roughing electrodes, followed by a finishing electrode that brings it to its final size.[a]

Why CNC

Computer-based numerical control more than simplifies the production of all instructional tape fed into the control of a machining center; it adds the kind of flexibility lacking in NCs, whose tapes once punched are awkward to modify. With CNC, the tape is simply the output of an easily editable program developed from the work plan. Dimensions and instructions are keyed into the computer or fed in from tape, if available. (Tapes can be read from off-line programmers and from CAD/CAM systems.)

Hundreds of combinations of cutting parameters can be preprogrammed, stored in the computer's memory, and called up at any time. Hundreds more can be programmed by the operator for automatic switching at different stages in the cutting program. Adaptive controls are available to override programmed instructions to minimize the chance of arcing when machining.

Many steps ordinarily performed by a skilled operator (including setup) are simplified by the use of the computer's software. For example, functions automatically performed by the program are tool-offset compensation and scaling, edge and center finding, and automatic electrode indicating.

CNCs[b] can run up to five axes simul-

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[a] Joel Frados, *Plastics Engineering Handbook*, Fourth Edition, Van Nostrand Reinhold (1976).

[b] Including in EDMs made by Sodick Inc., Woodbury, NY.

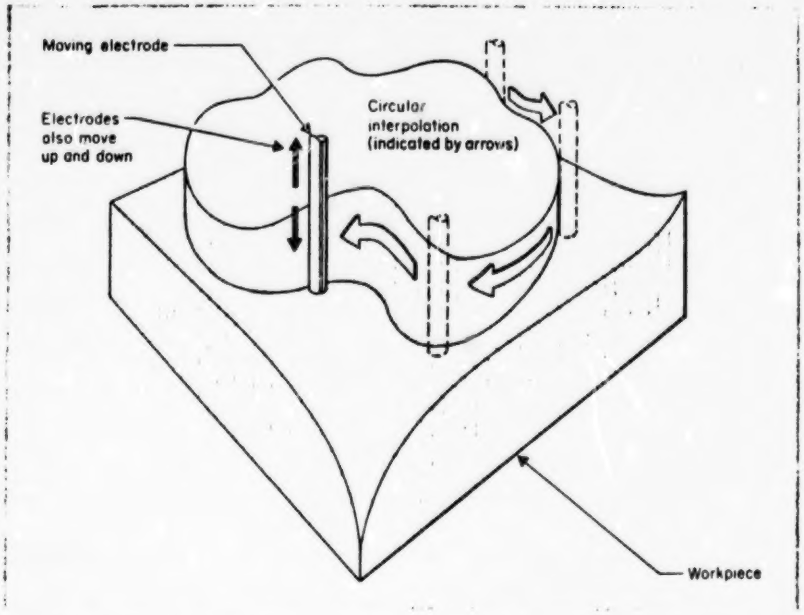

Moving electrode
Electrodes also move up and down
Circular interpolation (indicated by arrows)
Workpiece

Figure 5. Circular interpolation (path of movement) of the electrode in three axes contours workpieces, providing precise erosion and mirror finish.

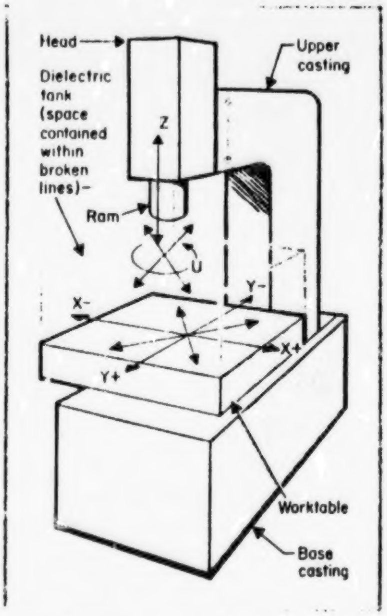

Head
Upper casting
Dielectric tank (space contained within broken lines)–
Z
Ram
U
X-
Y-
X+
Y+
Worktable
Base casting

Figure 6. Axes of motion are X, Y and Z in planes plus U for rotational motion.

taneously. The basic axes are X, Y, Z, and U – the last, a rotating and rotary indexing axis on the quill). (See *Fig. 6.*) A fifth axis can be used for such operations as rotating or indexing the workpiece from the table.

Controls can therefore perform three-axis and switchable-plane circular interpolation. For example, any of the three linear axes (X, Y, or Z) can be programmed to run simultaneously with the U-axis to cut helical gears or threads. Ordinary orbiting operations, in circular, square, or straight-line patterns, and in continuous-path patterns (independent of programmed interpolation)—(see *Fig. 7*)—can be programmed to generate tapers, expand threaded holes, and perform similar special functions. Thus such controls are capable of automatically running a program of simple instructions, changing cutting parameters and electrodes as the machining (eroding process) job moves from one part of a job to another.

Wirecut EDM

For high-precision machining of carbide or steel molds and dies, wirecut EDM machines under CNC can deliver fine finishes, permit long-term unattended operation, and, when equipped with a water or oil dielectric system (one switching automatically to the other), contribute to the thermal stability of the workpiece.

Holes are started by a servo-controlled wire containing quill carrying a small tubular electrode. Wire to each hole is subsequently advanced and its end annealed and straightened by a threading mechanism before it is passed through the start hole. Broken wires are rethreaded automatically.

To improve workpiece thermal stability during the eroding operation, and hence the accuracy of the cut, the workpiece is submerged in an oil or water dielectric (whose temperatures are held at constant levels). Rough cutting is done under water; fine finishing under oil.

To adjust to variations in workpiece thickness, the axis carrying the upper wire guide can be programmed to move (up or down) accordingly. Simultaneous changes in power-supply, feedrate, and wire-tension commands are similarly programmed. The third and fourth axes control the wire angle by moving the lower guide.

All of the machine functions are controlled by a CNC capable of carrying a great number of sets of cutting parameters (including subroutines) that can be called up at any time. Through a built-in optical tape reader, the CNC can be programmed by punched tape in various formats using conventional APT language. ☐

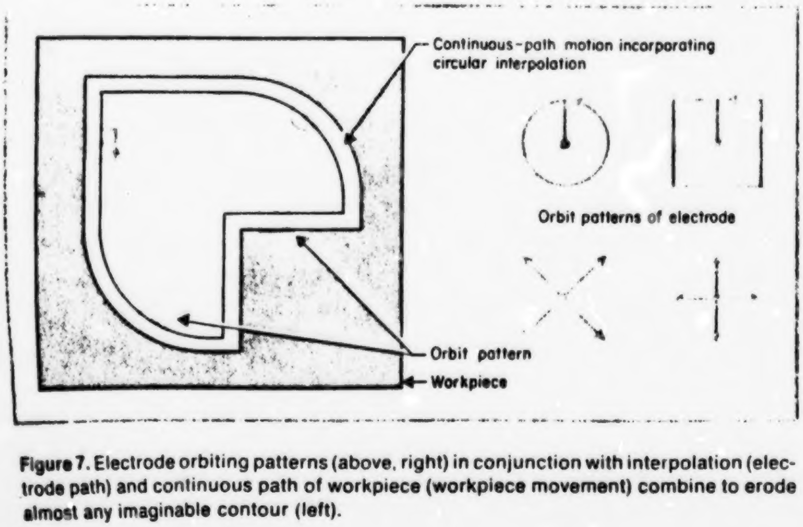
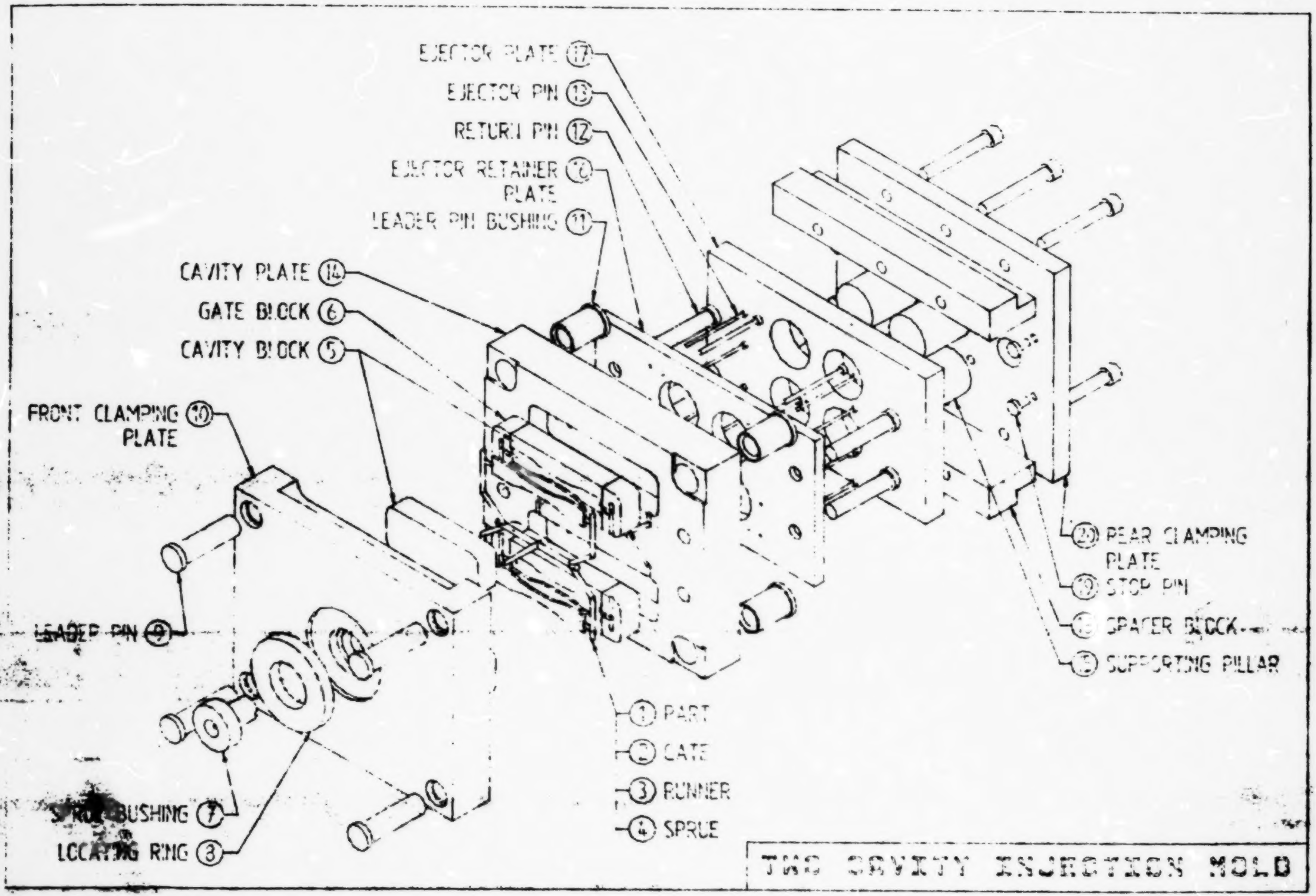

Continuous-path motion incorporating circular interpolation
Orbit patterns of electrode
Orbit pattern
Workpiece

Figure 7. Electrode orbiting patterns (above, right) in conjunction with interpolation (electrode path) and continuous path of workpiece (workpiece movement) combine to erode almost any imaginable contour (left).


EJECTOR PLATE (17)
EJECTOR PIN (13)
RETURN PIN (12)
EJECTOR RETAINER PLATE (16)
LEADER PIN BUSHING (11)
CAVITY PLATE (14)
GATE BLOCK (6)
CAVITY BLOCK (5)
FRONT CLAMPING PLATE (10)
LEADER PIN (9)
SPRUE BUSHING (7)
LOCATING RING (3)
(1) PART
(2) GATE
(3) RUNNER
(4) SPRUE
(20) REAR CLAMPING PLATE
STOP PIN
SPACER BLOCK
SUPPORTING PILLAR

TWO CAVITY INJECTION MOLD

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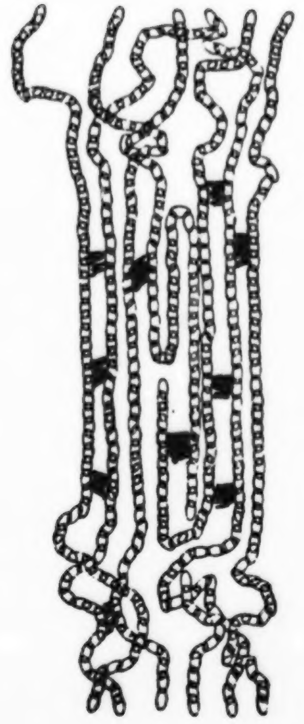
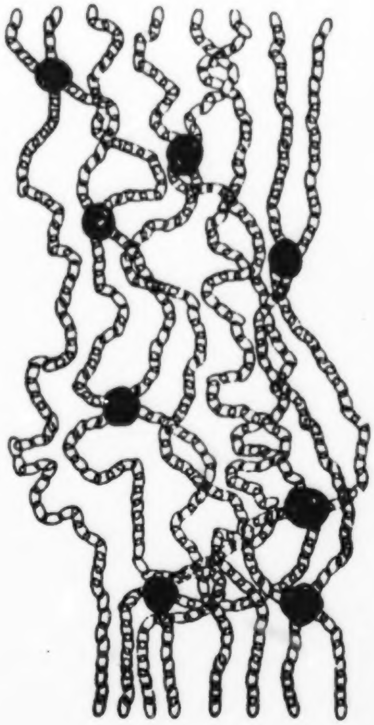
P. van Gheluwe

Plastics

HEAT

Thermoplastics	Thermosets
soften } heating	soften } heating
melt } heating	melt } heating
harden cooling	harden } heating
	infusible

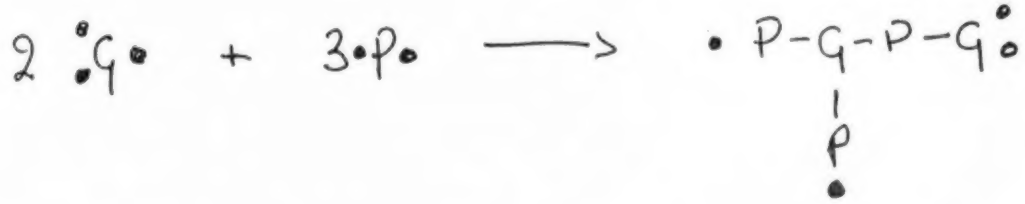


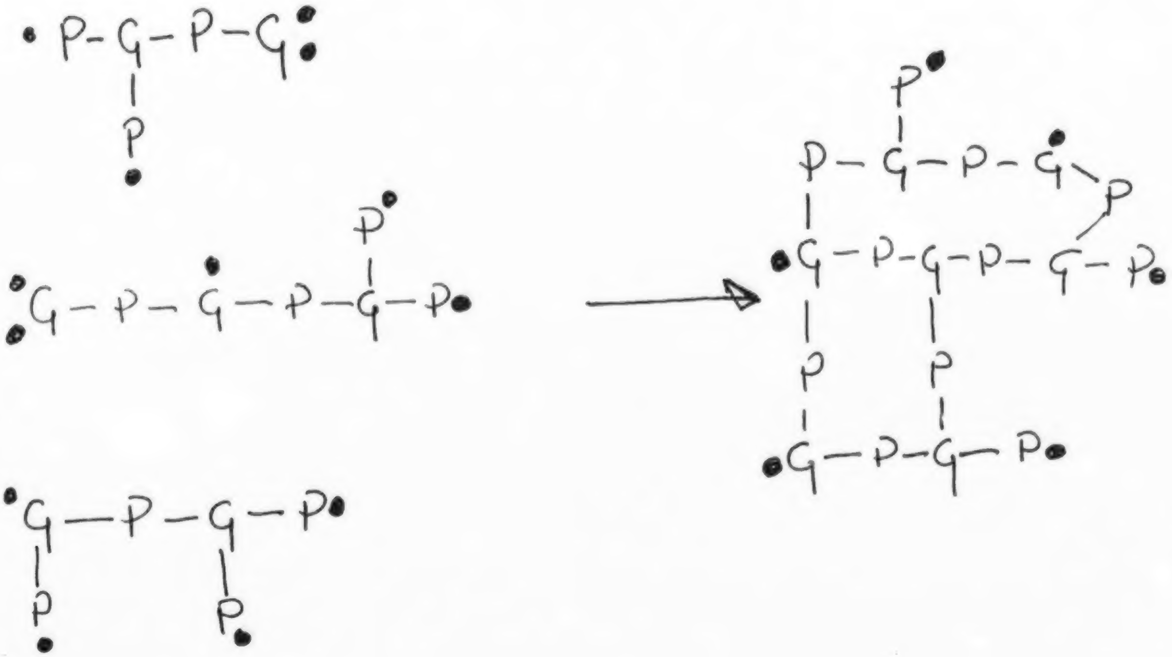


Polymerization and cross-linking

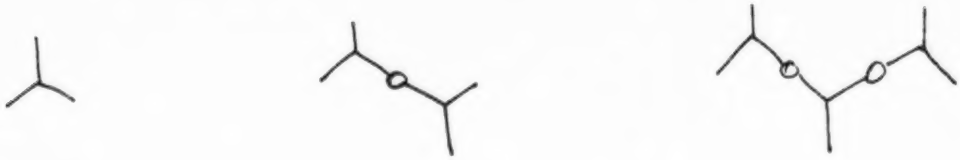
difunctional monomers: •P•

trifunctional monomers: :G•





Multifunctional monomers

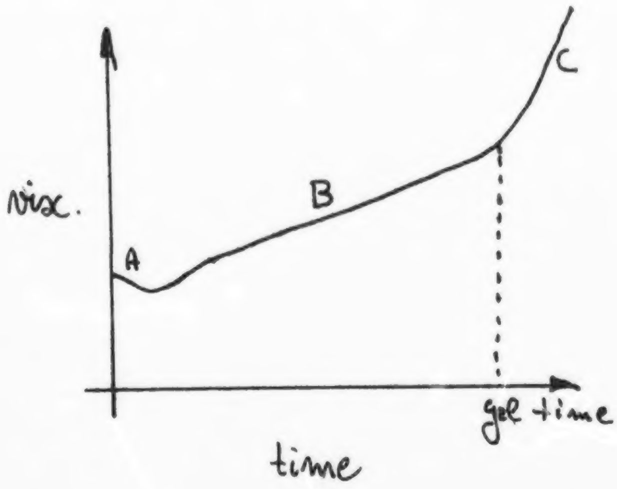


- the polymer has more functional groups than the monomer

- larger molecules grow more rapidly.

- gel point.

Gel time and cure time



How does the molecular weight progress?

A~A B~B
A~A B~B

$$DP = \frac{\text{initial \# of groups}}{\text{\# of groups not reacted}}$$

	DP
A~AB~B + A~A B~B	$8/6$: 1.33
A~AB~BA~A + B~B	$8/4$: 2
A~AB~BA~AB~B	$8/2$: 4

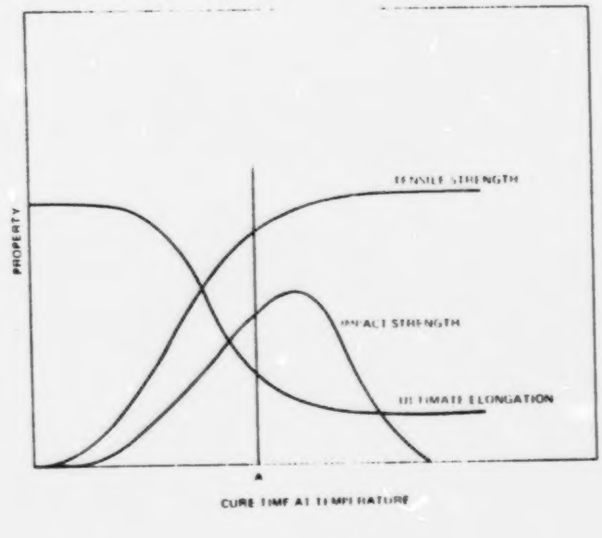
$$\boxed{DP = \frac{1}{1-p}}$$

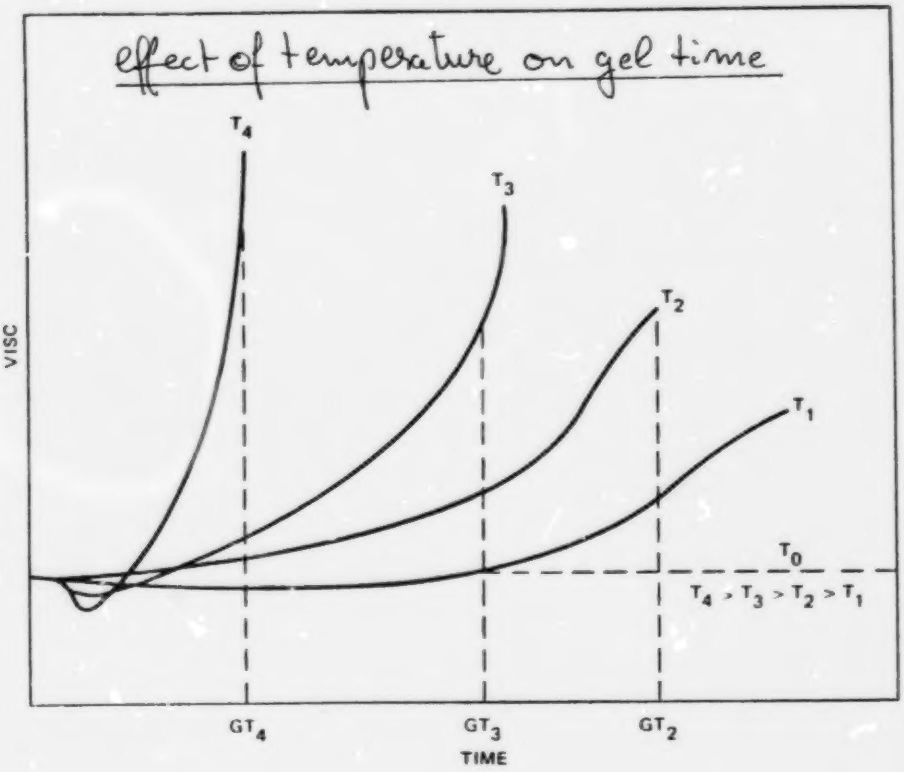
p	DP
0.75	4
0.90	10
0.95	20
0.98	50
0.99	100
0.995	200
0.998	500
0.999	1000

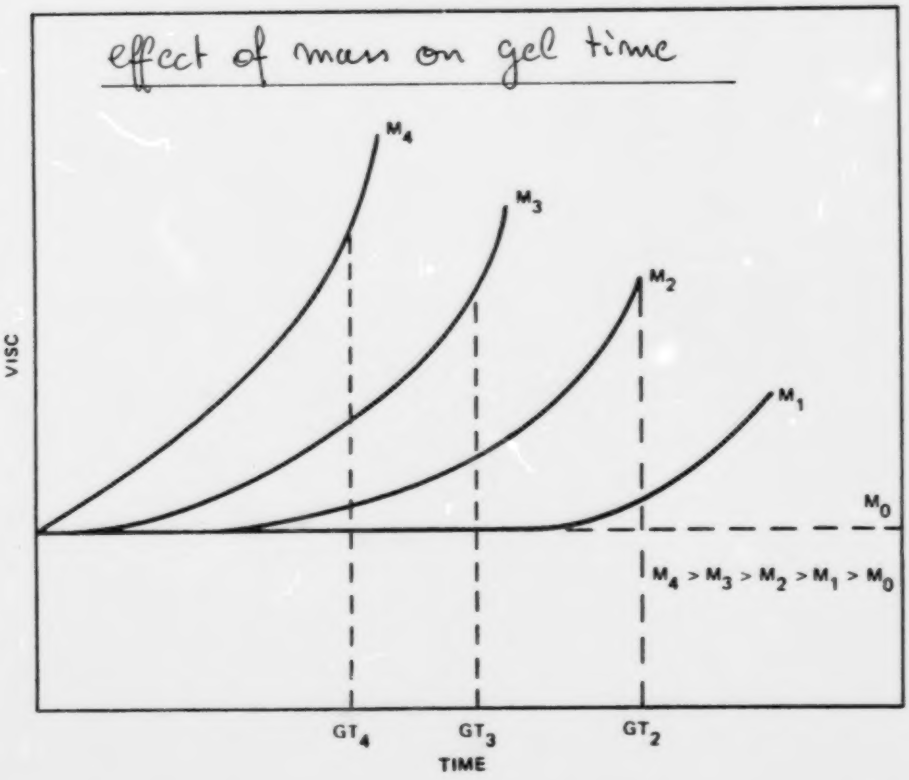
Shelf life - Working life - Pot life.

- catalyst level
- solids content
- degree of advancement
- temperature < storage / working.

Determination of cure time

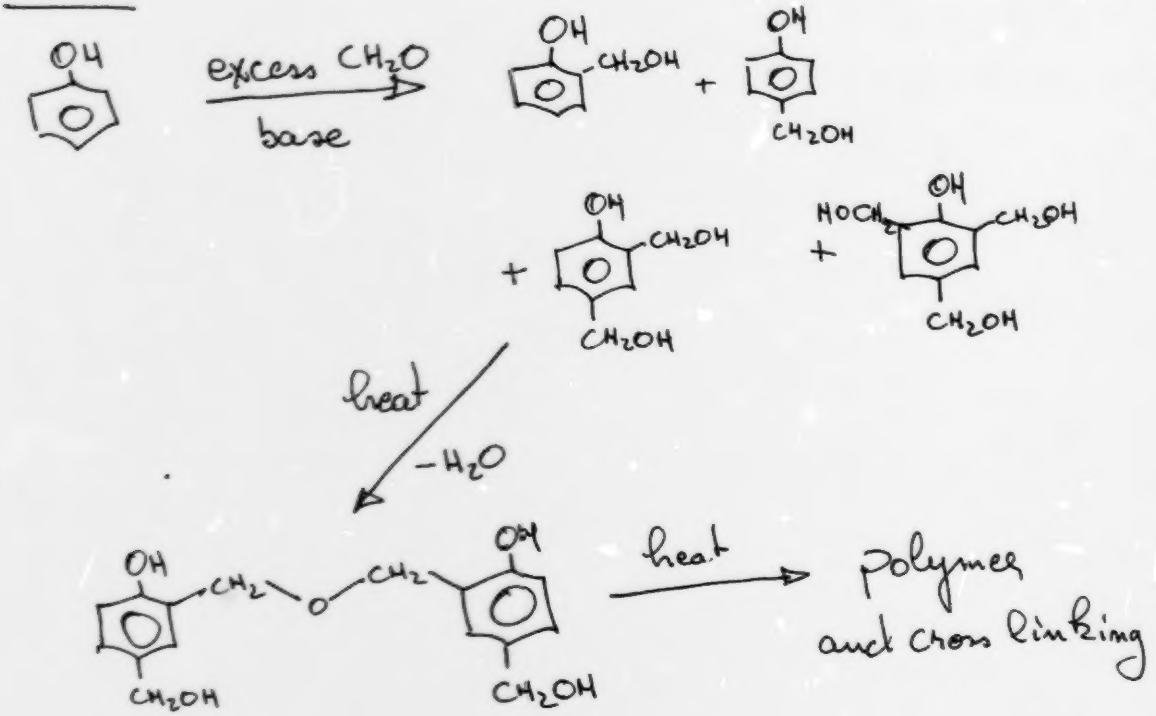



effect of temperature on gel time

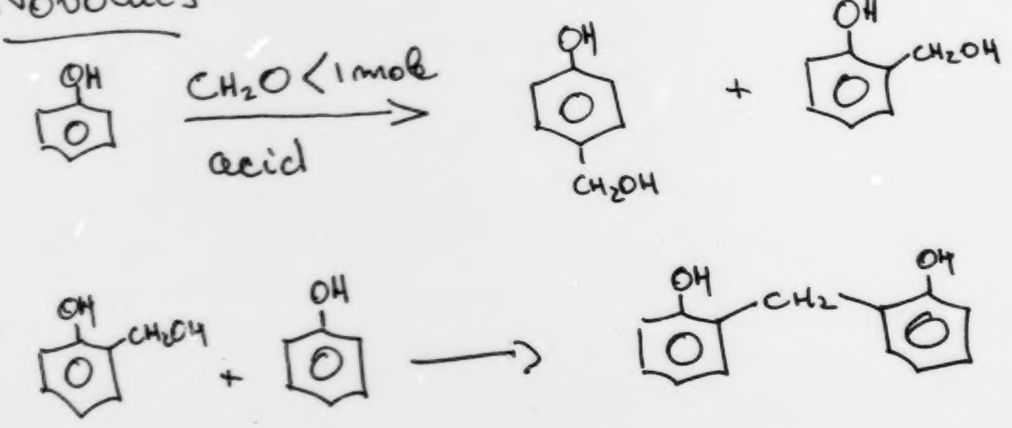

effect of mass on gel time

Preparation and structure of phenolic resins

Resols


OH
excess CH₂O
base
OH
CH₂OH
+
OH
CH₂OH
+
OH
CH₂OH
CH₂OH
+
OH
HOCH₂
CH₂OH
CH₂OH
heat
−H₂O
OH
CH₂
O
CH₂
OH
CH₂OH
CH₂OH
heat
polymer
and cross linking

Novolacs

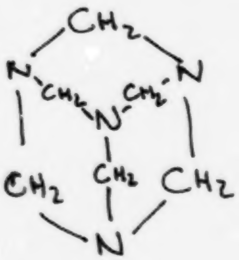

OH
CH₂O < 1 mole
acid
OH
CH₂OH
+
OH
CH₂OH
OH
CH₂OH
+
OH
OH
CH₂
OH

Resols will polymerize as such under heat

$$2 \sim\phi\text{-}CH_2OH \xrightarrow{<150^\circ C} \sim\phi\text{-}CH_2\text{-}O\text{-}CH_2\text{-}\phi\sim + H_2O$$

$$2 \sim\phi\text{-}CH_2OH \xrightarrow{>150^\circ C} \sim\phi\text{-}CH_2\text{-}\phi\sim + CH_2O$$

Novolacs need a catalyst



$$\underset{\Delta}{\overset{6H_2O}{\rightleftharpoons}} 6CH_2O + 4NH_3$$

"hexa"

$$\text{-}(CH_2O\text{-})_m \underset{\Delta}{\rightleftharpoons} m\ CH_2O$$

"para"

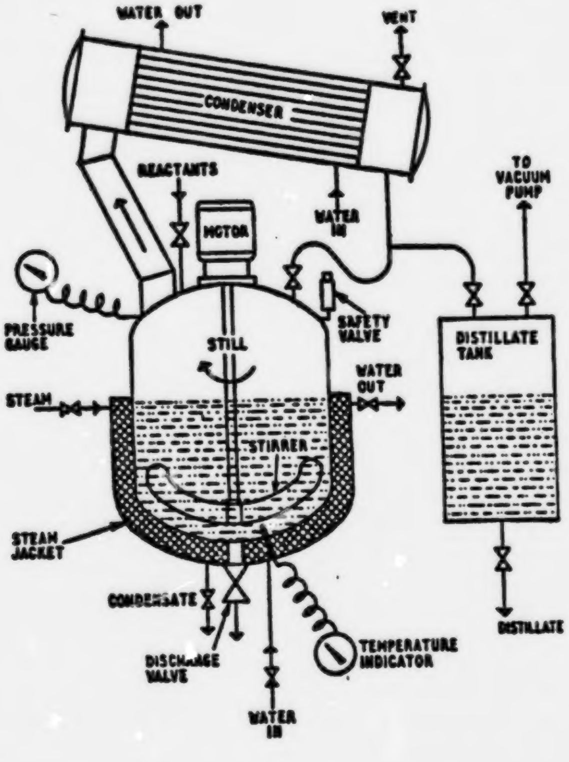
Stages in thermoset polymerization

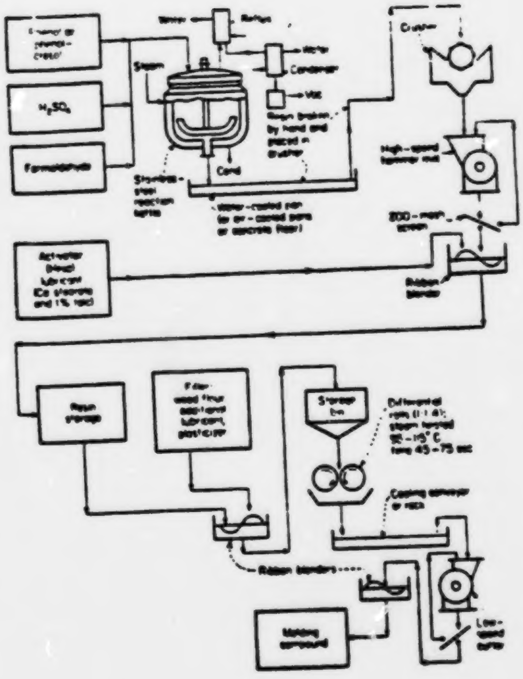
A- stage : liquid, soluble polymer of low molecular weight.

B- stage : solid, slightly soluble polymer melts and flows under heat and/or pressure

C- stage : solid, infusible cross linked network.

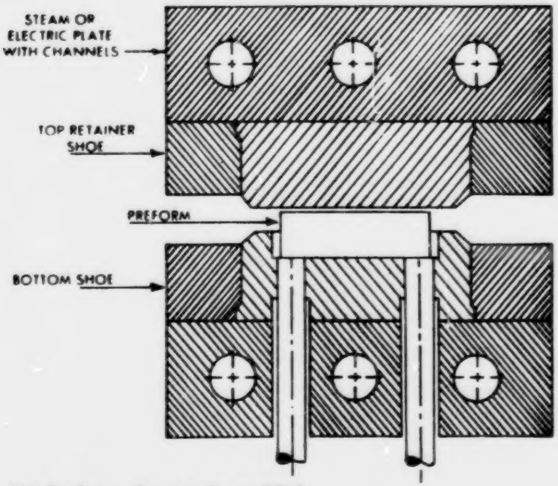
Resin kettle for thermoset preparation


WATER OUT
VENT
CONDENSER
REACTANTS
TO VACUUM PUMP
WATER IN
MOTOR
PRESSURE GAUGE
SAFETY VALVE
STILL
DISTILLATE TANK
STEAM
WATER OUT
STIRRER
STEAM JACKET
CONDENSATE
DISCHARGE VALVE
TEMPERATURE INDICATOR
DISTILLATE
WATER IN

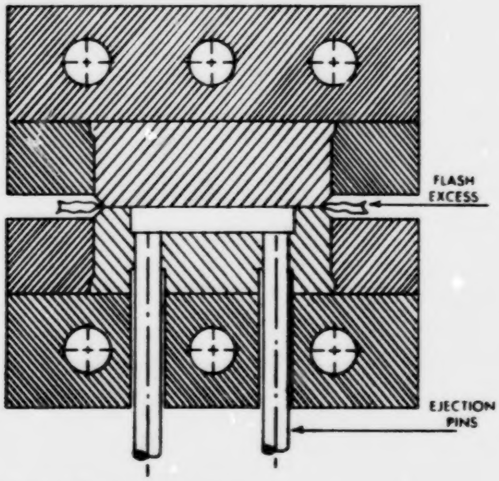

Phenol or cresol
H_2SO_4
Formaldehyde
Water
Reflux
Steam
Water
Condenser
Vac
Resin broken by hand and placed in crusher
Stainless-steel reaction kettle
Cool
Water-cooled pan (or air-cooled pans or concrete floor)
Crusher
High-speed hammer mill
200-mesh screen
Ribbon blender
Activator (Hexa) lubricant (Ca stearate and 1% lime)
Resin storage
Filler: wood flour additional lubricant, plasticizer
Storage bin
Differential rolls (1:1.4); steam heated 95–115 °C time 45–75 sec
Cooling conveyor or rack
Ribbon blenders
Low-speed cutter
Molding compound

Applications

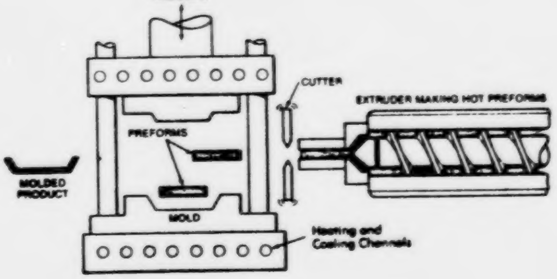
- Molding resins < compression molding
  injection molding.


STEAM OR ELECTRIC PLATE WITH CHANNELS
TOP RETAINER SHOE
PREFORM
BOTTOM SHOE

(A) Preform about to be molded.


FLASH EXCESS
EJECTION PINS

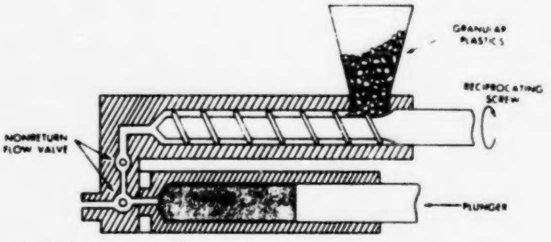
(B) Closed mold, showing flash.


HYDRAULIC PRESSURE
CUTTER
EXTRUDER MAKING HOT PREFORMS
PREFORMS
MOLDED PRODUCT
MOLD
Heating and Cooling Channels

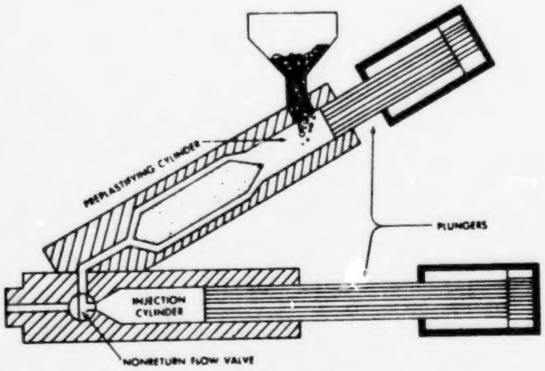
Fillers Used with Phenolics.

1. Organic fillers–all have relatively poor heat resistance.
   a. Wood flour–cheapest and commonest; good appearance and flow; poor to fair electrical properties; fair impact and good tensile strength; low heat conductivity.
   b. Walnut-shell flour–smooth surface with medium gloss.
   c. Cotton flock–improves impact but reduces flow.
   d. Chopped textile fabric–improves impact even more, but flow becomes poorer.
   e. Twisted cord–highest impact with good flow; poor water absorption.
   f. Rubber–questionable whether this addition should be listed as a filler since, when the rubber and phenolics are used together, a conventional filler such as wood flour, cotton flock, or asbestos is also added; improvements in impact and flexibility.
2. Inorganic fillers–have some advantages over organic fillers, but are not as widely used except for special-purpose molding powders; better dimensional stability, water absorption, heat resistance, and chemical resistance compared with wood flour and other cellulose fillers.
   a. Asbestos–good heat resistance, chemical resistance, and water resistance; lowers flexibility and tensile strength and increases specific gravity.
   b. Diatomaceous silica–good appearance, heat resistance, and electrical properties; very abrasive.
   c. Mica–excellent electrical properties, heat resistance, and dimensional stability; does not wet well; causes sticking and poor mold release.
   d. Graphite–improved frictional properties; electrical resistance decreases.
   e. Fibrous glass–good impact and electrical properties; good high-temperature resistance.

injection molding


GRANULAR PLASTICS
RECIPROCATING SCREW
NONRETURN FLOW VALVE
PLUNGER

(A) Simple schematic of screw machine.


PREPLASTIFYING CYLINDER
PLUNGERS
INJECTION CYLINDER
NONRETURN FLOW VALVE

(B) Simple schematic of plunger machine.

Phenolics

Advantages

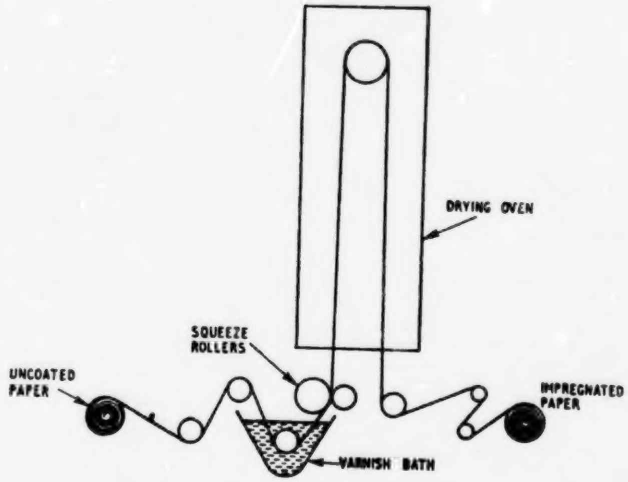
- low cost
- resist at high temp.
- solvent resistance
- rigid
- good compressive strength
- electrical properties
- self extinguishing

Disadvantages

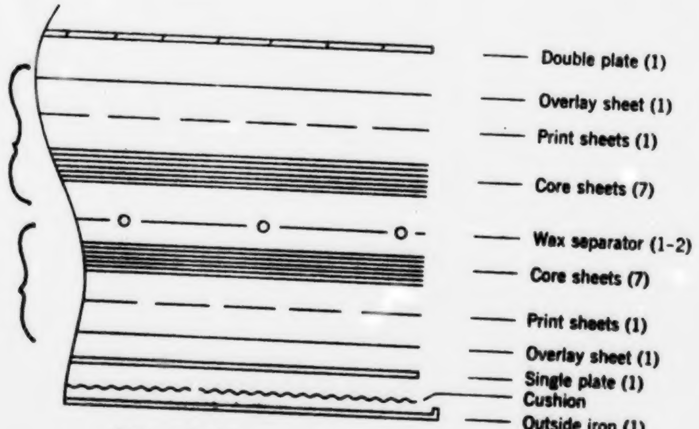
- need fillers
- attacked by bases + oxidizers.
- volatiles during cure
- dark color.

- Laminating resins

* use resoles


DRYING OVEN
SQUEEZE ROLLERS
UNCOATED PAPER
IMPREGNATED PAPER
VARNISH BATH

- paper or fabric as a reinforcement
- laminates are used as insulating materials
- circuit boards
- core of decorative laminates < Arborite™ / Formica™.

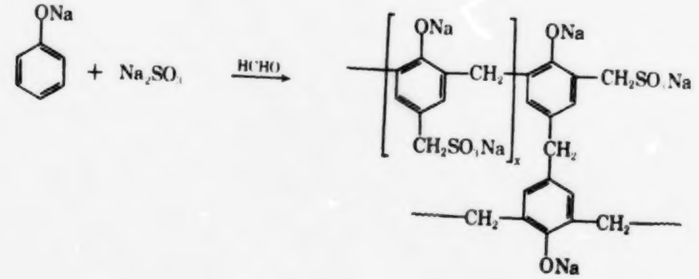

Double plate (1)
Overlay sheet (1)
Print sheets (1)
Core sheets (7)
Wax separator (1-2)
Core sheets (7)
Print sheets (1)
Overlay sheet (1)
Single plate (1)
Cushion
Outside iron (1)

Schematic diagram of laminate buildup arranged for pressing.

- Bonding resins
  * mostly novolac
  * brake linings, grinding wheels
  * glass and rock-wool fibre insulation bonding.

- Coatings + Adhesives
  * resoles
  * wire enamels, reservoir coatings
  * plywood, wood composites.

- Ion exchange resins

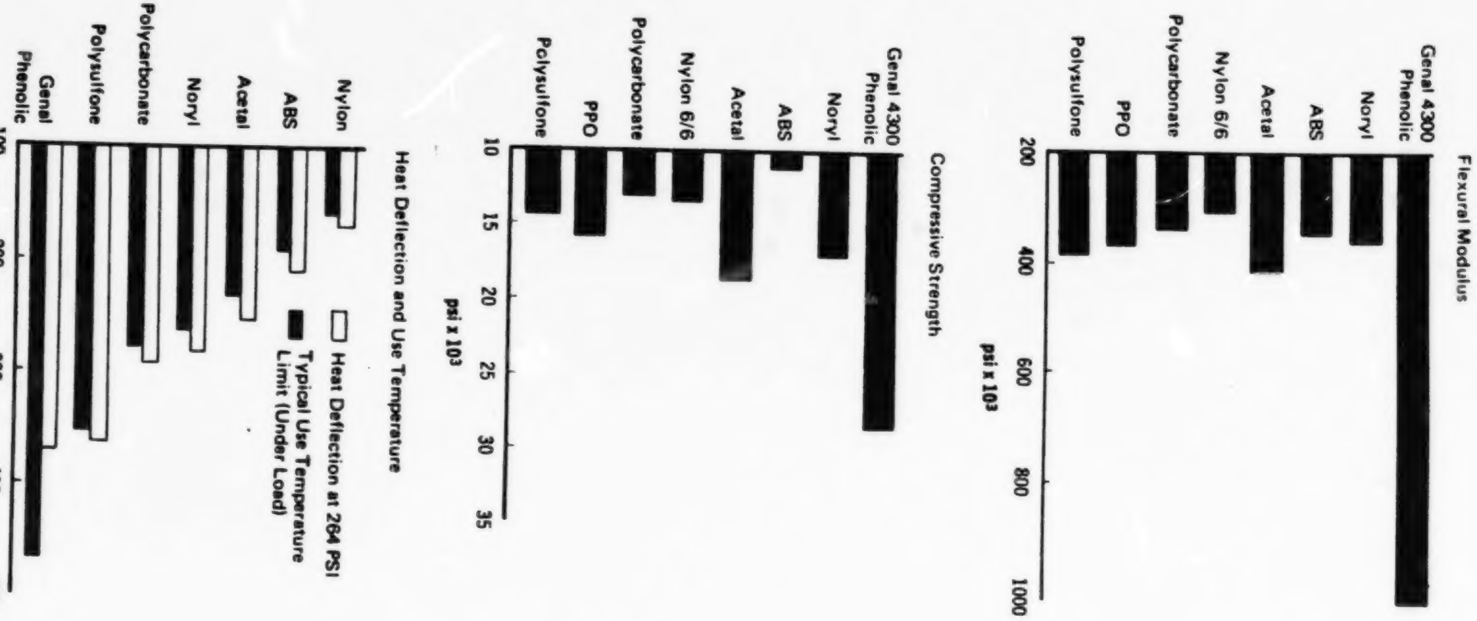

ONa
+ Na2SO3
HCHO
ONa
CH2
CH2SO3Na
x
ONa
CH2SO3Na
CH2
CH2
CH2
ONa

- Phenolic foams
  * liquid resole + acid catalyst and blowingagent.
  * flame retardant insulation panels

Comparative Properties of Phenolics and Other Thermosets.*

	Alkyd		Allylic (DAP)		Epoxy		Melamine		Phenolic		Polyester Premix		Silicone		Urea	
Density, lb/cu in.	0.08	–	0.05	–	0.07	–	0.05	–	0.06	–	0.06	–	0.07	–	0.05	–
Flexural strength, 1000 psi	8	15	10	20	12	60	10	23	10	45	6	25	7	18	10	18
Flexural modulus of elasticity, 10^5 psi	20	28	7	13	22	30	15	19	10	33	7	20	14	25	14	–
Tensile strength, 1000 psi	4	10	5	7	9	25	6	10	7	21	–	–	4	6	7	–
Impact strength, ft-lb/in. notch	0.4	12	1	6	0.4	30	0.3	12	0.3	27	3	24	0.3	10	0.3	–
Hardness (Rockwell)	M116	–	M108	–	M110	–	M120	–	M112	M120	M45	M100	M89	–	M118	–
Volume resistivity, ohm-cm	10^{14}	–	10^{14}	10^{16}	9×10^{15}	–	10^{13}	–	10^{11}	10^{13}	10^{12}	10^{14}	10^{14}	–	10^{11}	–
Dielectric strength (short-time), v/mil	375	–	375	400	375	–	320	430	300	425	345	420	350	400	350	–
Dielectric constant (10^6 cps)	5	4.2	4	3.3	4.75	–	5.7	–	5.5	4	5.2	6.4	3.8	–	6.6	–
Dissipation factor (10^6 cps)	0.017	0.014	0.02	0.01	0.013	–	0.03	0.02	0.05	0.005	0.008	0.022	0.006	0.005	0.03	–
Arc resistance, sec	140	180	100	160	123	–	120	186	35	180	140	180	300	420	130	–
Max cont service temperature, F	275	300	325	500	400	500	210	400	300	550	250	300	500	700	170	–
Flammability	Yes	Self-ex	Yes	Self-ex	Yes	Self-ex	Self-ex	–	Yes	Self-ex	Yes	Self-ex	Yes	Self-ex	Self-ex	–
Colorability	Yes	–	Poor	–	Yes	–	Exc	–	Poor	–	Yes	–	Yes	–	Exc	–

*Riley, 1962. Value in left-hand column = mean average for general-purpose grades. Value in right-hand column = generally accepted high value in compounds formulated to optimize that particular property. Data are only typical and approximate, and not representative of specifications.



Comparative properties of injection-moldable phenolics and other engineering thermoplastics. (*Courtesy: General Electric Co.*)

aminoplastics

$\swarrow$ UF $\qquad$ $\searrow$ MF

- * commercialization 50 - 60 years ago
- * old technology but varied applications
- * polymers based on nitrogen

natural gas

$\downarrow$

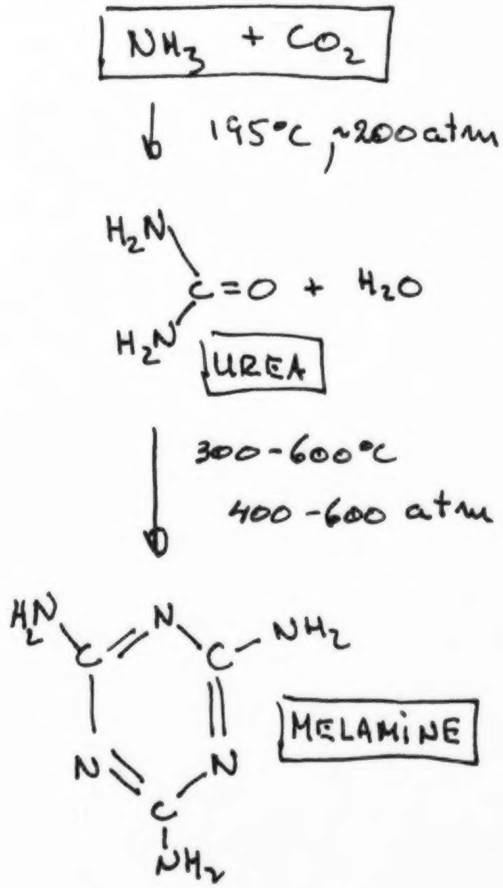
CH_4 methane

$\downarrow \leftarrow O_2$

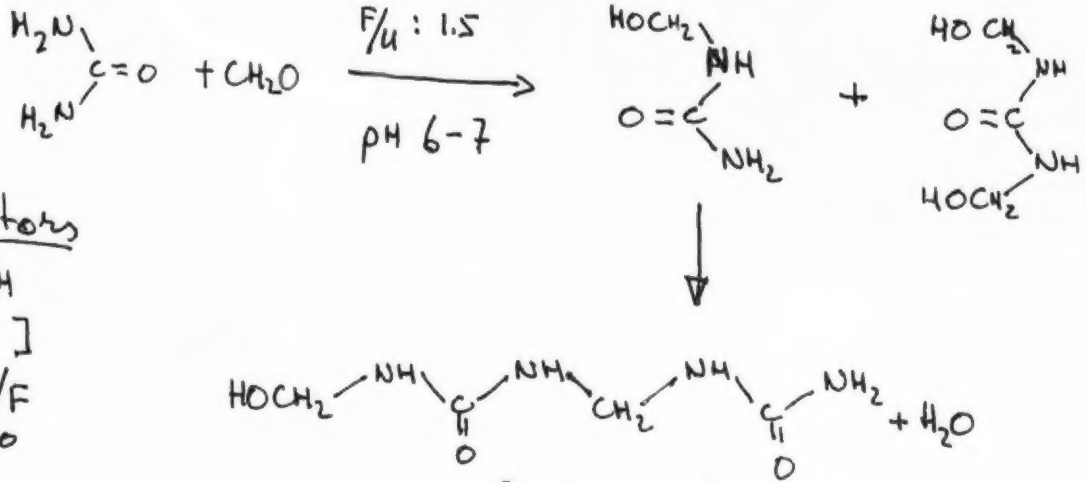
CH_3OH methanol

$\downarrow \leftarrow O_2$

CH_2O formaldehyde


NH3 + CO2
195°C, ~200atm
H2N
H2N
C=O + H2O
UREA
300-600°C
400-600 atm
H2N
N
C
NH2
N
N
C
NH2
MELAMINE

Preparation of UF and MF resins

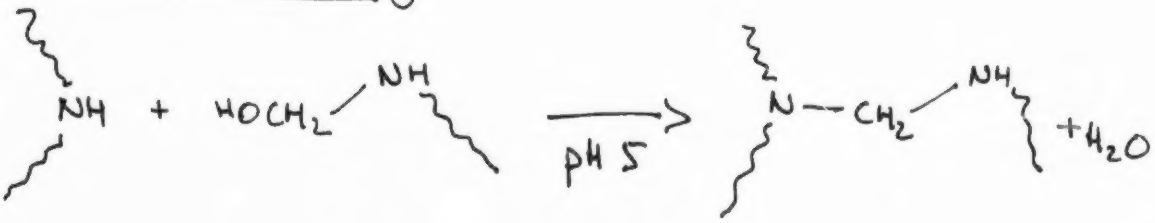


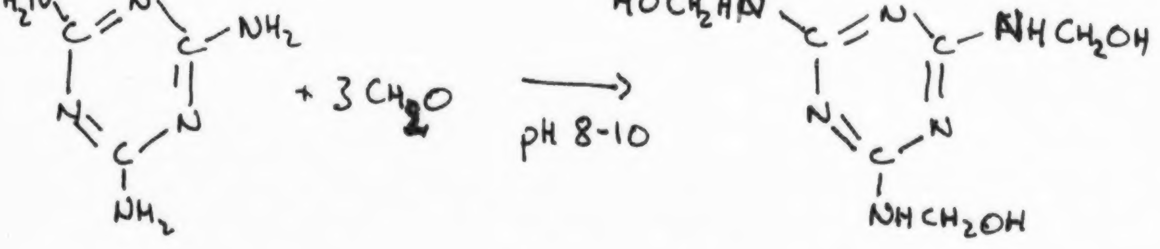
linear polymer

factors

pH
[ ]
u/F
T°
t

cross-linking





trimethylol melamine

Cross-linking : same as with ureas.

Applications of UF & MF resins

- Molding compounds

* fillers : α cellulose (best for coloring)

* wide variety of pigments.

* same processes as with phenolics
- compression
- transfer
- injection

* conditions: (roughly)

T° : 125 - 165°C

P : 2000 - 8000 psi
20000 psi (transfer)

t : 20-60 sec (longer for MF)

* products: electrical fittings - buttons - knobs
bottle caps - handles - dinnerware
appliance housings.

Properties of mouldings prepared from urea–formaldehyde and melamine–formaldehyde moulding compositions (Testing according to BS 2782)

Property	*Units*	*Urea-formaldehyde*				*Melamine-formaldehyde*			*Melamine-phenolic*	*G.P. phenolic*
		α-cellulose filled	*Woodflour filled*	*Plasticised*	*Translucent*	*Cellulose filled*	*Glass filled*	*Mineral filled*		
Specific gravity	—	1·5–1·6	1·5–1·6	1·5–1·6	~1·5	1·5–1·55	~2·0	~1·8	1·5–1·6	1·35
Tensile strength	10^3 lbf/in^2	7·5–11·5	7·5–11·5	7–9·5	7–10	8–12	6–10	4–6	6–8	8
	MPa	52–80	52–80	48–66	48–69	55–83	41–69	28–41	41–55	55
Impact strength	ft lbf	0·20–0·35	0·16–0·35	0·16–0·24	0·14–0·2	0·15–0·24	0·16–0·23	0·12–0·22	0·12–0·15	0·16
Cross-breaking strength	10^3 lbf/in^2	11–17	11–16·5	13·5–15·5	13–17	13–21	9–14	6–11	10–12	11·5
	MPa	76–117	76–114	93–107	89–117	89–144	62–96	41–76	69–83	80
Dielectric strength (90°C)	V/0·001 in	120–200	60–180	100–200	70–130	160–240	150–250	200–250	30–150	75–175
Volume resistivity	Ω m	10^{13}–10^{15}	10^{13}–10^{15}	10^{14}–10^{15}	—	10^{9}–10^{10}	10^{15}–10^{16}	10^{15}–10^{16}	10^{11}–10^{12}	10^{12}–10^{13}
Water absorption										
24 h at 20°C	mg	50–130	40–170	50–90	50–100	10–50	10–20	7–14	—	—
30 min at 100°C	mg	180–460	250–600	300–450	300–600	40–110	20–35	15–40	—	—

* Advantages ——— Disadvantages

Advantages
- good hardness & scratch resistance
- low cost
- easy to color
- self extinguishing
- solvent resistance
- food contact
- low water absorption
- electrical properties
- heat resistance

Disadvantages
- must be filled
- poor oxidation stability
- acids and bases attack
- F↑ under humid conditions if poor cure.

- Laminating Resins
  * strichtly melamine
  * saturate then dry a paper web
  * laminate @ $\left\langle \begin{matrix}\text{high}\\ \text{low}\end{matrix} \right\rangle$ pressure
  * hardness - clarity - stain resistance
  * countertops, furniture, vertical applications.
- Adhesives
  * mostly urea (melamine for outstanding properties)
  * gluing veneers (thickeners added)
  * particleboard (10% resin).

- Coating Resins
  - * alcohol modified
  - * usually baked
  - * stove & refrigerator enamels.

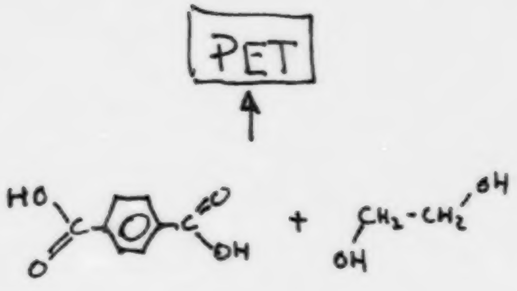
- Other applications
  - * textiles: crease proofing, shrinkage control flame proofing (phosphorus)
  - * paper industry: wet strength resins.

- Foams

* urea resin + foaming agents + catalyst
* foaming machine mixes components with air
* the foam is poured into the void
* set time: 20 secs, cure time: 2-4 h.
* drying time 1-2 days.
* density: ~ 0.75 lb/ft^3 (10 - 14 kg/m^3)
* K: 0.24 - 0.18 BTU in/ft^2 h °F
* self extinguishing.
* problems < incomplete cure / hydrolysis => free F

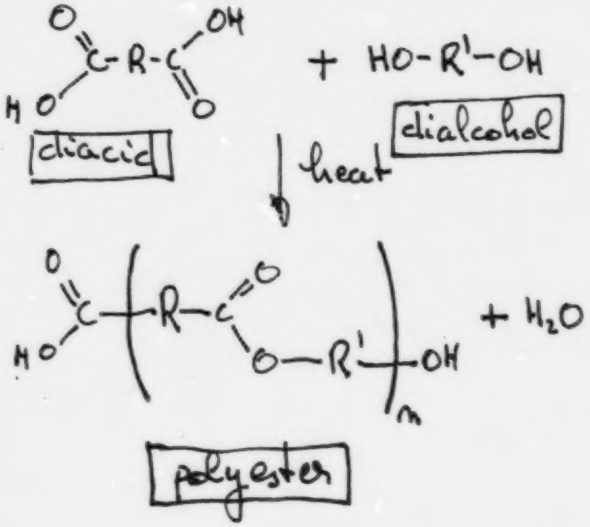
Polyesters

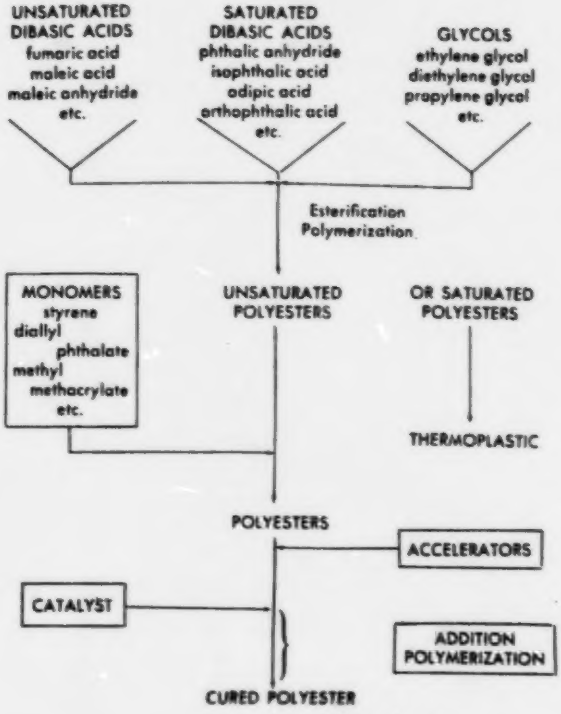
- Thermoplastic
  (saturated)


PET
HO
O
C
C
O
OH
+
CH₂-CH₂
OH
OH

*beverage bottles
*fibers (Dacron™ Fortrel™)
* films (Mylar™)

- Thermoset
  (unsaturated)
  ↳ permits X-linking
  → double bonds


O
OH
C-R-C
HO
O
diacid
+ HO-R'-OH
dialcohol
heat
O
HO
C
R
C
O
O
R'
OH
n
+ H₂O
polyester


UNSATURATED DIBASIC ACIDS
fumaric acid
maleic acid
maleic anhydride
etc.
SATURATED DIBASIC ACIDS
phthalic anhydride
isophthalic acid
adipic acid
orthophthalic acid
etc.
GLYCOLS
ethylene glycol
diethylene glycol
propylene glycol
etc.
Esterification Polymerization
MONOMERS
styrene
diallyl phthalate
methyl methacrylate
etc.
UNSATURATED POLYESTERS
OR SATURATED POLYESTERS
THERMOPLASTIC
POLYESTERS
ACCELERATORS
CATALYST
ADDITION POLYMERIZATION
CURED POLYESTER

Unsaturated Polyester Components.

Components	Ingredients	Characteristics
Unsaturated anhydrides and dibasic acids	a–Maleic anhydride	a–Lowest cost, moderately high heat deflection temperature (HDT)
	b–Fumaric acid	b–Highest reactivity (crosslinking), higher HDT, more rigidity
Saturated anhydrides and dibasic acids	a–Phthalic (orthophthalic) anhydride	a–Lowest cost, moderately high HDT, provides stiffness, high flex, and tensile strength
	b–Isophthalic acid	b–Higher tensile and flex strength, better chemical and water resistance
	c–Adipic acid, azelaic acid, and sebacic acid	c–flexibility (toughness, resilience, impact strength); adipic acid is lowest in cost of flexibilizing acids
	d–Chlorendic anhydride	d–Flame retardance
	e–Nadic methyl anhydride	e–Very high HDT
	f–Tetrachlorophthalic anhydride	f–Flame retardance
Glycols	a–Propylene glycol	a–Lowest cost, good water resistance and flexibility, compatibility with styrene
	b–Dipropylene glycol	b–Flexibility and toughness
	c–Ethylene glycol	c–High heat resistance, tensile strength, low cost
	d–Diethylene glycol	d–Greater toughness, impact strength and flexibility
	e–Bisphenol-A adduct	e–Corrosion resistance, high HDT, high flex and tensile strength
	f–Hydrogenated bisphenol-A adduct	f–Corrosion resistance, high HDT, high flex and tensile strength
Monomers	a–Styrene	a–Lowest cost, high reactivity, fairly good HDT, high flex strength
	b–Diallyl phthalate	b–High heat resistance, long shelf life, low volatility
	c–Methyl methacrylate	c–Light stability, good weatherability, fairly high HDT
	d–Vinyl toluene	d–Low volatility, more flexibility, high reactivity
	e–Triallyl cyanurate	e–Very high HDT, high reactivity, high flex and tensile strength
	f–Methyl acrylate	f–Light stability, good weatherability, moderate strength

Properties of Various Peroxide-Accelerator Systems for Polyesters.

Property	Benzoyl peroxide + tertiary amine	Ketone peroxide + cobalt	Ketone peroxide or hydroperoxide + vanadium
Potlife			
Polyester and peroxide	Long	Short	Short
As above + accelerator	Long	Long	Short
Gel time	Variable	Variable	Short
Cure	Fast	Moderate	Very fast
Sensitivity to:			
Air inhibition	Strong	Moderate	Strong
Moisture	None	Strong	Strong
Glass finish	None	Faint	Moderate
Filler and pigment	Seldom	Mostly strong	Reacts with oxides, hydroxides, carbonates, etc.
Color after curing	Faint	Faint	Moderate
Discoloration			
By light	Strong	None	None
By heat	Strong	Faint	Faint

Applications

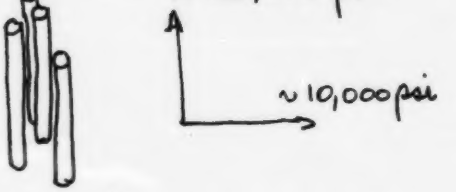
molding or coating

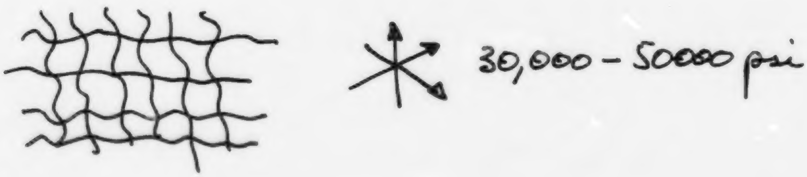
↓ glass reinforced ↓ alkyd-based paints

Properties
- flexural strength
- tensile strength
- strength/weigth

Laminates

	tensile strength
* resin :	~ 10,000 psi
* glass filament:	180,000 - 300,000 psi


~150,000 psi
~10,000 psi


30,000 – 50000 psi

Molding

closed
(press molding)

Process
- * injection
- * compression
- * resin transfer
- * pultrusion

Materials

BMC, DMC, SMC, TMC

liquid resin

Production
- high volume
- machine + tool cost

open
(contact molding)

Process
- * hand layup
- * sprayup
- * filament winding.
- * centrifugal casting
- * bag molding.

Materials

liquid resin
and glass fiber.

Production
- low volume
- labor costly.

Polyester Properties.

Property	Thermoplastic Polyester	Thermosetting Polyester (Cast)	Thermosetting Polyester (Glass Cloth)
Molding qualities	Good	Excellent	Excellent
Specific gravity (density)	1.37-1.38	1.10-1.46	1.50-2.10
Tensile strength (psi)	10,400	6000-13,000	30,300-50,000
Compressive strength (psi)	18,600	13,000-36,500	25,000-50,000
Izod, impact (ft-lb/in)	0.8	0.2-0.4	5.0-30.0
Hardness, Rockwell	R120, M94	M70-M115	M80-M120
Thermal expansion (10^{-5}/°C)	6	5.5-10	1.5-3
Resistance to heat (°F)	175-250	250	300-350
Dielectric strength (volts/mil)	350-400	380-500	350-500
Dielectric constant (60 Hz)	3.65	3.0-4.36	4.1-5.5
Dissipation factor (60 Hz)	0.0055	0.003-0.028	0.01-0.04
Arc resistance (seconds)	40-120	125	60-120
Water absorption (24 hrs, %)	0.02	0.15-0.60	0.05-0.50
Burning rate (in/min)	Slow burning	Burns—self-exting.	Burns—self-exting.
Effect of sunlight	Discolors slightly	Yellows slightly	Slight
Effect of alkalies	Attacked by oxidizing acids	Attacked by oxidizing acids	Attacked by oxidizing acids
	Attacked	Attacked	Attacked
Effect of solvents	Attacked by halogen hydrocarbons	Attacked by some	Attacked by some
Machining qualities	Excellent	Good	Good
Optical	Transparent-opaque	Transparent-opaque	Translucent-opaque

Polyesters

Advantages

- wide curing latitude
- high filler levels
- tooling inexpensive (liquids)
- fire resistance (modified)
- liquid ⇒ wetting + flow
- many processing techniques
- ease of property modification

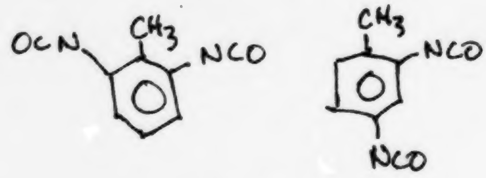
Disadvantages

- low service temp (~200°F)
- poor solvent resistance.

Polyurethanes

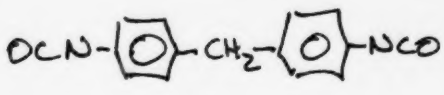
Raw Materials and Chemistry

"izo"



TDI (20:80)

(toluene diisocyanate)



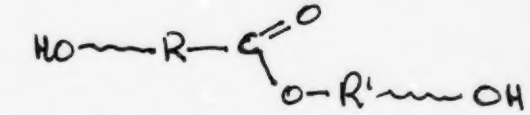
MDI

(methylene diphenylisocyanate)

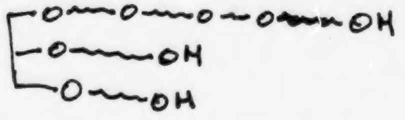
(diphenylmethane-4,4'-diisocyanate)

Polyol

- polyester polyol



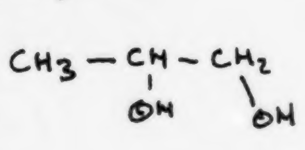
- polyether polyol



Chain extender

$HO-CH_2-CH_2-OH$ EG

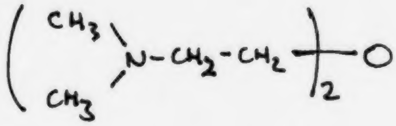
$H_2N\sim\sim NH_2$



$CH_3-CH(OH)-CH_2-OH$ PG

amines

Catalysts

- amines 

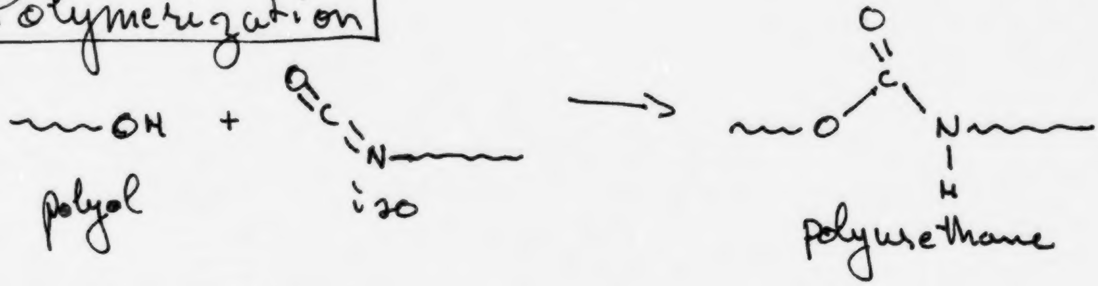
$$\left(\begin{matrix}CH_3\\CH_3\end{matrix}\!\!>N-CH_2-CH_2\right)_2O$$

- tin $Sn(O_2C-R)_2$

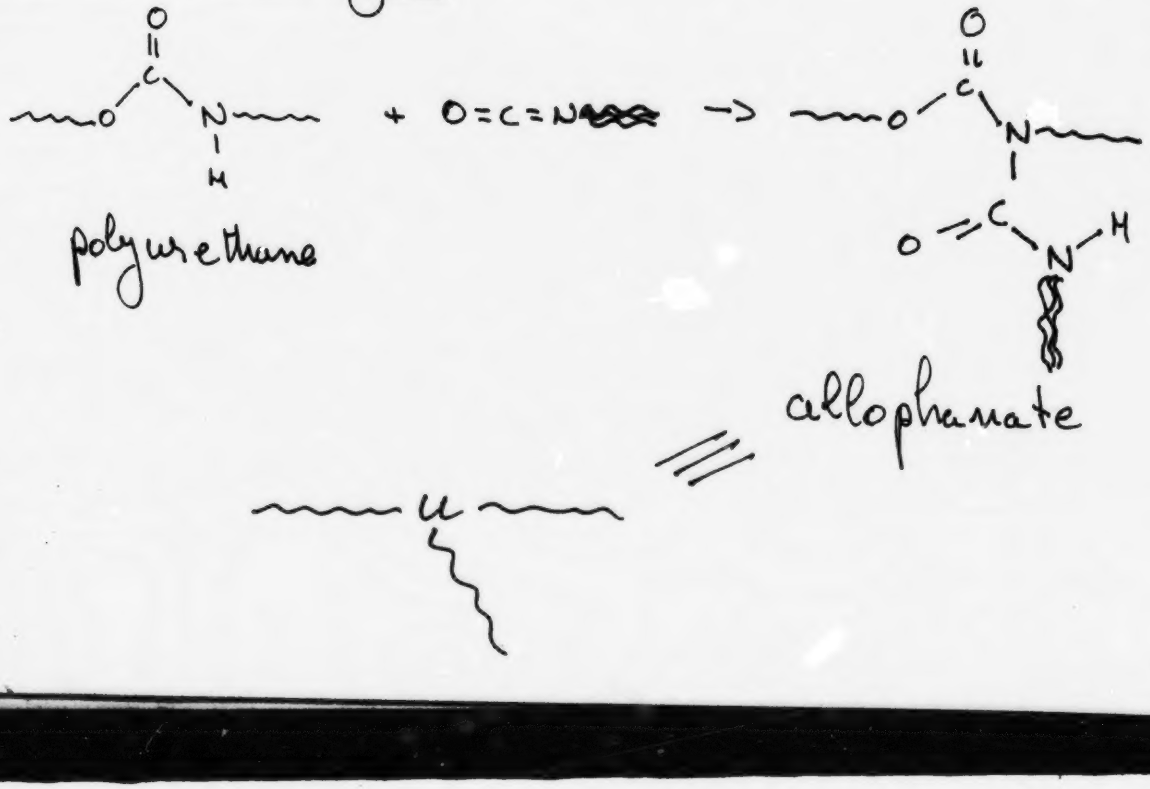
Surfactant

- silicone foam stabilizer.

Polymerization


OH
polyol
iso
polyurethane

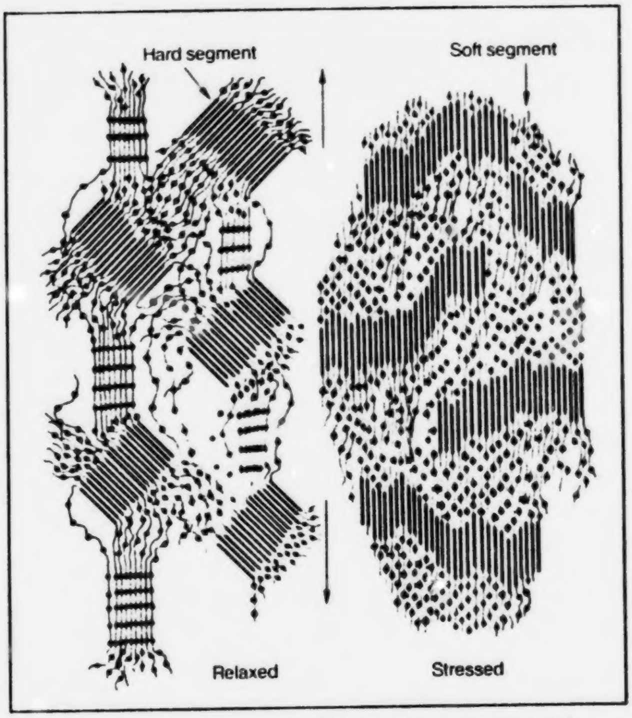
Crosslinking


polyurethane
O=C=N
allophanate
≡

Property Modification

- polyol type
- type and amount of extender
- isocyanate

* segmented structure of polyurethanes.


Hard segment
Soft segment
Relaxed
Stressed

Segmented Structure of Polyurethanes (schematic)

Cristalline aggregates

- thermal history
- tensile history
- reaction kinetics.

domains

hard segments

* X-talline, organized
* hydrogen bonding

Properties affected

* modulus
* hardness
* tear strength
* upper use T°

soft segments

* amorphous, entangled.

Properties affected

* elastic nature
* lower use T°

Advantages

- abrasion resistance
- good performance at low T°
- facile property modification
- ambient curing.
- relatively low cost
- foamable.

Disadvantages

- poor high T° service
- isocyanates are toxic.
- poor weatherability.
- attacked by acids & bases
- yellowing.

Product types and applications

Elastomers
- casting — TS — potting
- injection — TP+TS — skiboots, bumpers
- millable & vulcanizable — TS — tires (machinery)

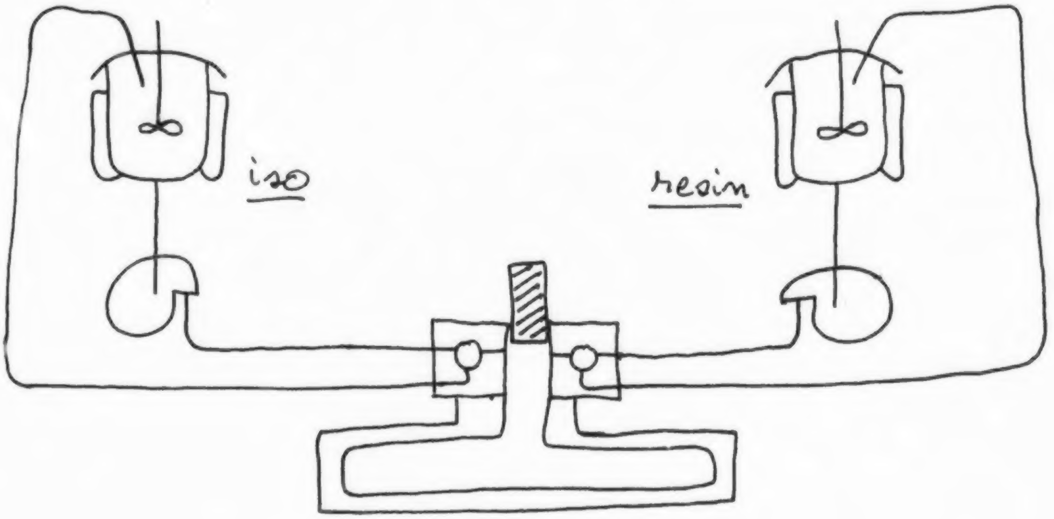
Foams
- flexible — TDI — TS — furniture
- semi-rigid — TS — automotive
- rigid — MDI — TS — insulation

Fibers
- nylon-like — TP
- elastic (spandex: Lycra(TM)) — TP

underwear
sportswear.

Adhesives + Coatings — TP+TS — shoe industry
floor finishes.

The Reaction Injection Molding Process



Components	Steps
- storage tanks	- blend + temper
- metering unit / pump \ cylinder	- dose
* 3000 psi * 1200 lb/min	
- mix head (impingement) (self cleaning)	- mix
- mold (< 100 psi, 60°c)	- inject - cure
- clamp (light, tiltable)	- eject
	- post cure.

RIM Process

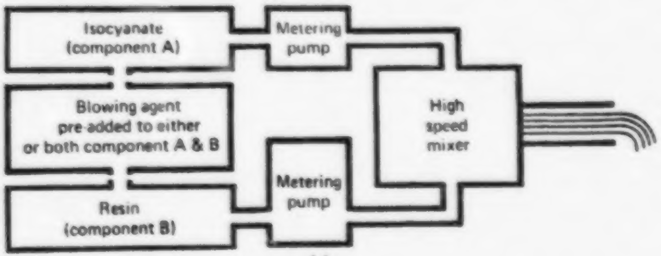
Advantages

- mold large parts (100lbs)
- short cycles (2-3min)
- low cost tooling
- wide property variation
  - all the advantages of PU
  - cellular (skin + core)
- fast cycles
- excellent surfaces
- low energy consumption

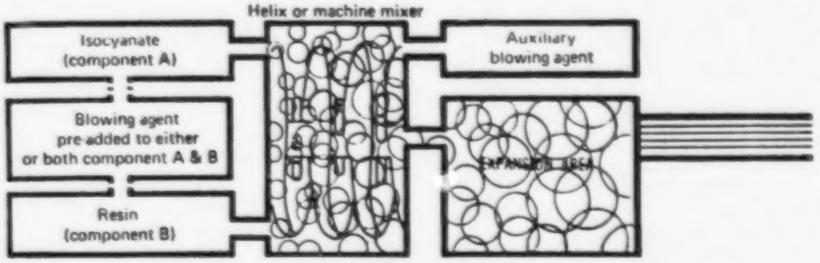
Disadvantages

- liquid handling
- new technology
- isocyanates
- technical problems. (chemistry + conditions)

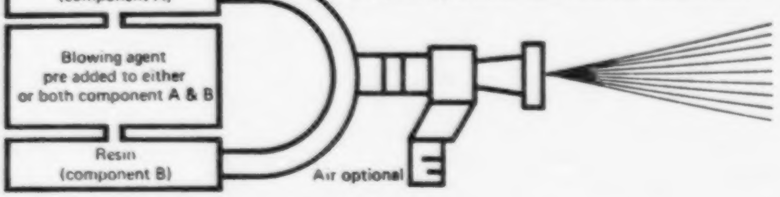
Urethane mixing techniques


Isocyanate (component A)
Metering pump
Blowing agent pre-added to either or both component A & B
High speed mixer
Metering pump
Resin (component B)

(a)

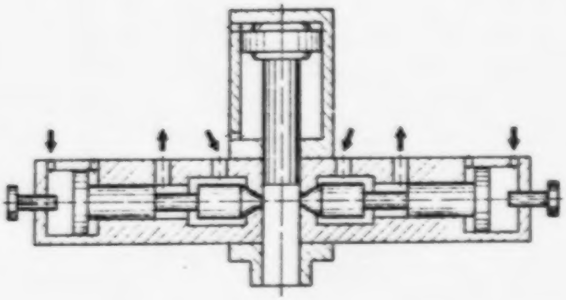

Helix or machine mixer
Isocyanate (component A)
Auxiliary blowing agent
Blowing agent pre-added to either or both component A & B
EXPANSION AREA
Resin (component B)

(b)

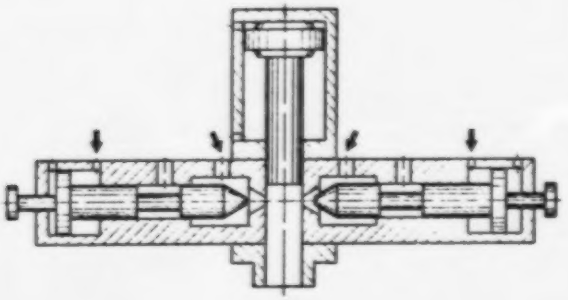

Isocyanate (component A)
Blowing agent pre added to either or both component A & B
Resin (component B)
Air optional

This special spray gun mixes and atomizes urethane chemicals in its spray head . . . an innovation that has been made possible with the perfecting of formulations with fast reaction rates.

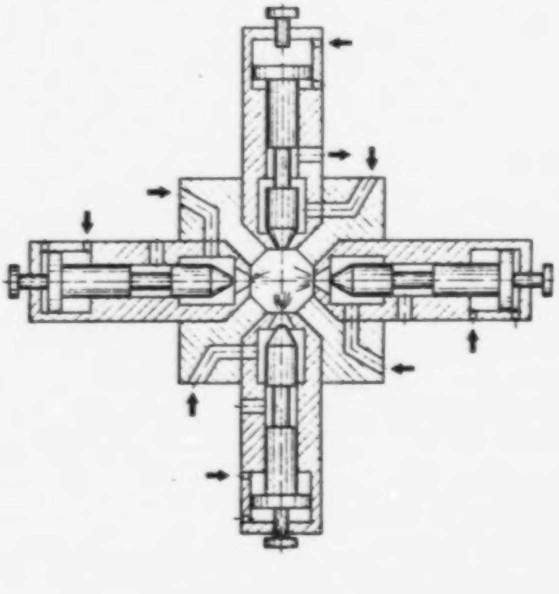
(c)



Circulation



Mixing



RIM Products

elastomers

elongation 75-120%

low mod. | high mod.

9000 -> 50,000 -> 140,000 psi

- * shoe soles
- * steering wheels
- * snowmobiles

glass reinforcement

high modulus elast. 130,000 psi $\xrightarrow[\text{milled glass}]{20\%}$ Reinforced 260,000 psi

* car fascia (integrated bumper, grill, head light).

structural foam

elongation 5-10%

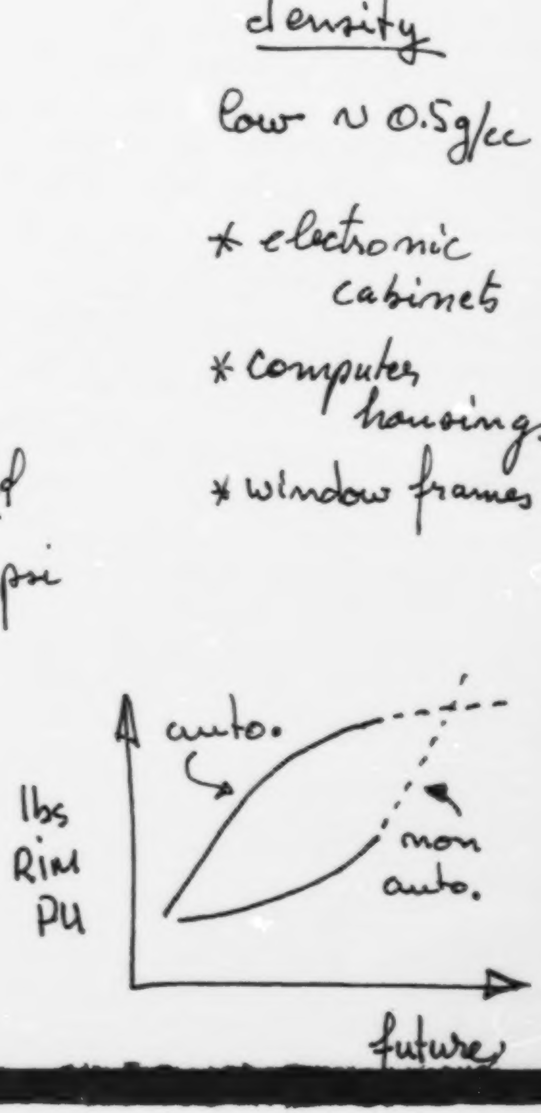
flex modulus

90,000 -> 180,000 psi

density

low ~ 0.5g/cc

- * electronic cabinets
- * computer housings
- * window frames.



Plastics Identification Table

By Dr. Hansjürgen Saechtling

Physical Properties

Pyrolysis, Solubility and Individual Identification Tests

Plastic Materials (arranged in chemical groups)			Density		Usual Appearance				Elastic Behavior			Sample slowly heated in pyrolysis tube m = melts d = decomposes al = alkaline n = neutral ac = acidic sac = strongly acidic	Reaction of gases given off	Ignition with small flame 0 = hardly ignitable I = burns in flame, extinguishes in absence of flame II = continues to burn after ignition III = burns vigorously, fulminates		Odor of gases given off on heating in pyrolysis tube or after ignition and extinction	Solubility in Cold Solvents s = soluble sw = swellable i = insoluble								Characteristic element, individual identification tests (Compare Chapter 4 "Testing for Heteroatoms", and Chapter 6 "Specific Identification Tests")
			unfilled	filled up to		solid products																			
Number	Standard Abbreviation (ISO 1043/ASTM 1600)	Name	g/cm³	g/cm³	transparent thin films	transparent, clear	hazy to opaque	usually contains fillers	leathery or rubbery, soft	flexible, resilient	hard						Gasoline	Benzene	Methylene chloride	Diethyl ether	Acetone	Ethyl acetate	Ethyl alcohol	Water	
6. Phenolic Resins **PF = Phenol/Formaldehyde, including cresol containing resins)**																									
6.1	PF	Free of filler uncured	1.25 to 1.3		industrial resins							m, d	n	I	difficult to ignite, bright, sooty	phenol, formaldehyde	i	i	i	i	s	i	s	(s)	
		molded or cast resins				(+)					+	d, cracks					i	i	i	i	i	i	i	i	
6.2.1	PF	Mineral filled moldings		1.8–2				+			+	d, cracks	n (al)	0/I	bright, sooty	phenol, formaldehyde, possibly ammonia									
6.2.2	PF	Organic filled moldings		1.4				+			+	d, cracks	n (al)	I/II	chars										
6.3.1	PF	Paper based laminates		1.3–1.4				+			+	d, delamination	n	II	bright, sooty	as above + burnt paper									
6.3.2	PF	Cotton based laminates																							
6.3.3	PF	Asbestos or glass fiber based laminates		1.8				+			+	d, cracks	n	0/I	reinforcing structure remains	phenol, formaldehyde									
7. Amino Resins (UF = Urea/Formaldehyde, MF = Melamine/Formaldehyde)																									
7.1	UF MF	uncured			glues								al	0/I	very difficult to ignite, flame slightly yellow, material chars with white edges	ammonia, amines, disgusting fishy odor (esp with thiourea), formaldehyde	i	i	i	i	i	i	i	s	N, possibly S
7.2.1	UF MF	Organic filled moldings		1.5				+			+	d, cracks, darkens, swells up					i	i	i	i	i	i	i	i	
7.2.2	MF	Mineral filled moldings		2.0				+			+														
7.2.3	MF + PF	Organic filled moldings		1.5				+			+														
7.3.1	MF	Glass fiber fabric based laminates		1.8				+			+														

Plastics Identification Table

By Dr. Hansjürgen Saechtling

Physical Properties

Pyrolysis, Solubility and Individual Identification Tests

Plastic Materials (arranged in chemical groups)			Density		Usual Appearance	solid products			Elastic Behavior			Sample slowly heated in pyrolysis tube m = melts d = decomposes al = alkaline n = neutral ac = acidic sac = strongly acidic		Ignition with small flame 0 = hardly ignitable I = burns in flame, extinguishes in absence of flame II = continues to burn after ignition III = burns vigorously, fulminates		Odor of gases given off on heating in pyrolysis tube or after ignition and extinction	Solubility in Cold Solvents s = soluble sw = swellable i = insoluble								Characteristic element, individual identification tests (Compare Chapter 8 "Testing for Heteroatoms" and Chapter 6 "Specific Identification Tests")
Number	Standard Abbreviation (ISO 1043/ASTM 1600)	Name	unfilled g/cm³	filled up to g/cm³	transparent thin film	transparent, clear	hazy to opaque	usually contains fillers	leathery or rubbery, soft	flexible, resilient	hard		Reaction of gases given off				Gasoline	Benzene	Methylene chloride	Diethyl ether	Acetone	Ethyl acetate	Ethyl alcohol	Water	
8. Crosslinked reaction resins (UP = unsaturated polyesters, EP = Epoxy resins)																									
8.1.1	UP	Unfilled cast resins (flame retarded)	~1.2 ≧1.3			+					+	darkens, m cracks, d possibly white deposit above	n (ac)	II (I)	bright yellow, sooty, softens if no filler, otherwise crackles, chars, filler or glass fiber residue	styrene and sharp additional odor	i	i	sw	i	sw	sw	i	i	ignitability depends also on fillers and pigments
8.1.2	UP	Moldings, laminates		1.4–2			+	+			+														
8.2.1	EP	Cast resins	~1.2			+					+	darkens from edge, d, cracks, possibly white deposit above	n or al	II I/II	difficult to ignite, burns with small yellow flame, sooty	depends on curing agent ester-like or amines (similar to PA), later phenol	i	i	sw	i	sw	sw	i	i	N with amine curing agents
8.2.2	EP	Moldings, laminates		1.7–2				+			+	(uncrosslinked)	(ac)												
9. Polyurethanes																									
	PUR	a) Crosslinked	1.26				+		+	+	+	m on strong heating, then d	al	II	difficult to ignite, yellow, bright foams, drips	typically unpleasant stinging (isocyanate)	i	i	sw	i	sw	sw	i	i	N
		b) Linear, rubberlike	1.17–1.22		+		+		+				ac	II			i	sw	sw	i	sw	sw	i	i	
10. Silicones																									
	SI	Mainly silicone rubber	1.25					+	+			d only on strong heating, white powder	n	0	glows in the flame	white smoke, finely divided white SiO_2 residue	sw	sw	sw	i	i	i	i	i	Si

PREPRINT NO. 3

THERMOSETS : MATERIALS & PROCESSES

Germain Belanger, Engineer
Germain Belanger, Plastics Consultant
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1 A- What are reinforced Plastics?

The term "reinforced Plastics" refers to a directed combination of a thermosetting resin and a reinforcement to produce a composite material, or laminate. The term "laminate" is meant to include all types of reinforced plastic shapes such as solid rods and bars, tube and pipe, structural shapes such as angles, channels and I-beams, flat sheets as well as housings or any unusual contoured shapes to meet a particular end-use application.

The designer or manufacturer can design or produce a reinforced plastic laminate whose mechanical properties in any given direction are both predictable and controllable. This can be done by carefully selecting the resin system to be used in terms of its desired end-use properties, and the reinforcement in terms of its composition and orientation in the finished product.

By working with these composite materials, resin and fiber glass, the designer or manufacturer is no longer limited by physical and chemical properties available from conventional natural materials.

The features to consider in evaluating an application for reinforced plastics?

1. Ease of producing simple and complex shapes as well as fabricating simple or complex structures.
2. An expeditious means of repair compared to replacement of the original material.
3. Lightweight
4. Simple installation
5. Machinability with ordinary hand tools
6. High strength-to-weight ratio

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7. Excellent cost-performance ratio
8. Minimum heat transfer or heat loss (insulating effect)
9. Nonconductivity (electrically insulating)
10. Little or no maintenance after installation
11. Noncontamination of product or process
12. Long service life.

1 B- Reinforced plastics as a structural material

Reinforced plastics can be tailored to satisfy a variety of specific end-use requirements, including wide temperature range, electrical insulation properties, corrosion resistance, and a spectrum of mechanical properties: tensile, flexural, and compressive strengths, impact strength, abrasion resistance, and hardness. Surface finishes can be highly refined. In many cases, colors can be molded in. Parts can be large or small, simple or complex. Consideration of many of these end-use requirements has led the designer to the proper choice of reinforcement, of resin system, and of process. These choices have been governed by the first three basic principles of designing with FRP.

1. Mechanical Strength: depends upon the amount and arrangement of the reinforcement.
2. Chemical, electrical and thermal performance result from selection and formulation of the resin system.
3. Material selection, plus design and production requirements, determine the process.

1 C- Corrosion mechanisms

The types of corrosion in reinforced plastics are limited and may be classed as:

1. Swelling
2. Destruction of the resin phase by chemical attack such as:
   a. Hydrolysis
   b. Oxidation
   c. Pyrolysis
3. Loss of adhesion between resin and reinforcement
4. Destruction of reinforcement - in the case of glass fibers by strong alkali or hydrofluoric acid.
5. Combination of 1,2,3 and 4.

Since reinforced plastics are heterogeneous in composition, corrosive attack may be confined to:

1. The resin phase
2. The interfacial area between the resin and the reinforcement
3. The reinforcement
4. A combination of the above

Metals corrode in an entirely different fashion. Of the 14 types of corrosion in metals and alloys listed in the literature, some of the more common types are:

1. General corrosion - where the thickness of metal is gradually reduced
2. Galvanic
3. Aerobic
4. Pitting
5. Dezincification
6. Graphitic and intergranular corrosion

Of the above forms of corrosion, reinforced plastics are only subject to oxidative attack.

The difference between the effects of corrosive agents on metals and reinforced plastics is important to those who specify equipment. If properly chosen for the service involved, reinforced plastics made by proper workmanship will last almost indefinitely. After a slight loss of strength during the initial period of use, reinforced plastics can be expected to remain stable and show little further deterioration of properties. Metals, on the other hand, will continue to react with the chemical environment and continue to deteriorate over a period of time.

Selection of reinforced plastics as well as other materials of construction should be based on the installed long-term cost-performance relationship and not on material cost comparisons alone.

2 A- Resins and resin systems

Resins used with fibrous reinforcements to produce reinforced plastics contribute chemical and thermal performance and prevent abrasion of the fibers by keeping them separated. The resin, in addition to forming an armor to protect the strength member, also serves as the adherent between adjoining fibers. By varying the resin ingredients and the reinforcing materials, many different products may be produced for a wide range of end uses.

Thermosetting and thermoplastic

Two main classes of resins are used in reinforced plastic products. They are called "thermosetting" and "thermoplastic". Thermosetting resin systems become hard when cured or when heated, and further heating will not soften them - the action is irreversible. Thermoplastic resins become soft when heated and hard when cooled - the action is repeatable.

Thermosetting resins undergo a chemical change or reaction called polymerization - the linking together of "monomers" to form "polymers". Time and temperature in the presence of catalysts or curing agents accomplish this reaction.

As mentioned earlier, two of the thermosetting resins primarily used for reinforced plastics applications are polyesters and epoxies.

Polyesters

Polyesters are considered the workhorse of the industry, accounting for about three-fourths of the thermosetting resins that are used in industry and about 90% or more of the resins used in the reinforced plastic industry. The word "polyester" is derived form two chemical processing terms - "polymerization" and "esterification".

Polyesters offer the advantage of a balance of good mechanical properties, chemical and electrical properties, dimensional stability, low cost and ease of handling.

Initially we can classify polyester resins into two major types:

1. General purpose resins

2. Special purpose resins

The general purpose polyester is a low-cost polyester, with good electrical and mechanical properties and reasonably good corrosion resistance.

Special purpose type polyesters are those resins which have been specifically formulated to meet some particular end-use requirement with respect to performance.

The formulation of special purpose polyesters involves the appropriate utilization of all the ingredients of the system, from the raw materials used to produce the basic resin, the reactive monomer for dilution and viscosity control, to the catalysts and accelerators involved in the cure.

Monomers

Polyesters as a solid material are blended with a reactive monomer to provide a workable resin material. Polyester resins as normally supplied by the manufacturer contain monomer but some polyesters may be purchased without monomer. Additional quantities of monomer may be added to the resin at the user's plant (in amounts recommended by the manufacturer) to reduce the viscosity.

Styrene is the ideal monomer and the most commonly used monomer in polyester resin systems because it is abundantly available, low in cost, has good solvent characteristics and reacts readily with the unsaturated polyester during the curing reaction.

The main functions of a monomer are:

1. To act as a solvent carrier for the unsaturated polyester
2. To modify the viscosity
3. To enhance selected properties with respect to the end-use application.
4. To provide a rapid means of reacting with the unsaturated linkages in the polyester to yield a completed reaction and cross-linked copolymer.

Catalysts

Organic peroxides are widely used to catalyze polyester resin systems and initiate the copolymerization reaction. More technically, the peroxides decompose to release free radicals. These free radicals are attracted to the points of unsaturation (reactive sites) in the monomer used to dilute the polyester, attack these active sites and initiate the polymerization reaction.

Three of the most common catalysts in use are methyl ethyl ketone peroxide, benzoyl peroxide and cumene hydroperoxide. Organic peroxides are popular because of convenience and cost in addition to facilitating control of the reaction (time of gelation and cure).

Polymerization or cure of polyester resin systems can also be achieved by exposure to radiation, ultraviolet light and heat. Some of the factors regulating catalyst choice are:

1. Desired temperature, allowable time of laminating operation
2. Type of monomer or mixture of monomer employed
3. Desired pot life
4. Desired gel and cure times
5. Influence of sunlight and weathering on product performance
6. Other specialized requirements of the finished end product influenced by the catalyst choice.

Accelerators

Accelerators are usually added to polyester resin formulations to initiate or speed the cure at room temperatures. When used in combination with catalysts, a rapid curing reaction can be started without the application of heat. Commonly used accelerators are cobalt naphthenate and diethyl aniline and dimenthyl aniline.

Fillers and pigments

Fillers and pigments are added to molding resins to:

1. Reduce shrinkage
2. Minimize crazing
3. Lower material costs
4. Impart color or opacity
5. Improve surface finish

Excessive use of fillers should be avoided as the fluidity of the resin can be reduced to a point where it will be difficult to handle. Use of fillers can make inspection for internal flaws difficult. Proper use to accomplish definite objectives can serve to an advantage.

2 B- Reinforcing materials

Drawn glass fiber is the major reinforcing material used in reinforced plastics in corrosion-resistant applications. Asbestos fibers, as well as synthetic fibers, are also used in corrosion-resistant laminates or components (such as pipe and fittings). There are a number of other reinforcements in use, which can be divided into five classes: metal reinforcements, inorganic fibers, wood and vegetable fibers, paper and natural or synthetic organic fibers.

Glass

The majority of glass reinforcing materials are made form two grades of glass which differ in chemical analysis - "E" and "C" glass. "E" grade is best applied for structural uses where high heat resistance and superior electrical properties are desired, and "C" grade for uses where superior resistance to chemical corrosion is required.

There are two basic forms of fiber glass reinforcements - continuous filaments, generally made from "E" glass, and staple fibers, generally made from "C" glass. Both forms of fiber glass begin with the same manufacturing process, but differ in the manner in which they are drawn from the glass furnace.

SUMMARY OF VARIOUS TYPES OF REINFORCEMENTS

Type of structure	Form	End-Use application
Continuous strand	Yarn Continous roving Spun roving	Filament winding Production of other reinforcement; Pultrusion products; Preforms
Cloth Fabrics	Various styles of weave	Laminate

Advantages:

1. Effective surfacing material to cover woven rovings and mats for better appearance and increased strength.
2. Exhibits good workability to eliminate excess resin and provides a high-glass content in laminate.
3. Provides good control of thickness and uniformity of glass content resulting in minimum deviation of physical properties.
4. Particularly suited for reinforcement in areas of high stress.

Type of structure	Form	End-Use application
Woven roving fabrics	Various styles of weave	Laminates

Advantages:

1. Good handling and drapability for use in hand lay-up
2. Provide a thicker build-up per ply of laminate than cloth
3. Provide a high glass content per ply
4. Exhibit high directional physical strength and moduli for orientation in areas of high stress.
5. Offer good impact resistance.

Chopped strands	Various lengths from 1/4" to over 3"	Preforms and molding compounds
Reinforcing Mats	Chopped strand or Continuous swirl	Laminates

Advantages:

1. Low cost per square foot per unit thickness
2. Balanced physical properties in all directions
3. Good interlaminar bond because of the interlocking of the fibers
4. Good handling and drapability in forming into complex contours.

Surfacing mats	Decorative overlay surfacing veils	Reinforcement of gel-coats; Special surface effects in laminates

Natural of synthetic organic fibers

Some of these fibers, particularly the synthetic organic types, are becoming more important in the reinforced plastics industry.

"Dynel"[12] is a synthetic fiber produced by extruding an acetone solution of acrylonitrile vinyl chloride copolymer. It is resistant to strong acids and extremely resistant to alkalies and many organic solvents. It has a comparatively low softening point of 250°F and is classed as self-extinguishing. Is is available in the form of fabrics and surfacing veils.

"Orlon"[13] is a synthetic fiber consisting primarily of acrylonitrile and is highly inert to strong acids, sunlight and the effects of weathering. It is generally resistant to moisture, organic solvents and weak alkalies and shows good resistance to mildewing and bacterial attack. It is comparatively strong, demensionally stable and slow-burning, with a softening point of 455°F. It is available in woven fabric of spun (continuous) roving.

"Dacron"[14] and "Tyrelene"[15] are linear polyester fibers and show toughness, strength and abrasion resistance. Chemically they are resistant to weak acids, alkalies and organic solvents, have a softening point of 450°F and are slow-burning. They are available as rovings, nonwoven fabrics or thin mats made from untwisted continuous yarn, and as woven and knitted fabrics when produced from continuous yarns.

2 C- Handling of reinforcement and resins

Thermoset resins come in a liquid form and are reactive chemicals, so they must be treated as reactive chemicals. The manufacturer's or supplier's safety instructions should be followed. Certain individuals, coming in contact with these resins may build up a sensitivity toward them. This sensitivity may cause a person to break out in a rash or hives if he is around the uncured resin. The cured resins are considered toxicologically inert and create no health problems in handling. They can cause dust problems during sanding or machining, especially if containing fillers such as glass, silica powder, asbestos, or metal powders.

Fiberglass can cause irritation to the individual if it is inhaled as dust or penetrates the skin.

Fillers vary in their degree of hazard from handling. Some, such as clays, may be considered non-hazardous. However, silica bearing powders, asbestos, and powdered metals may present health hazards from inhalation.

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[12] Dynel : Is a trademark of Union Carbide Corporation

[13] Orlon : Is a trademark of E.I. duPont de Nemours & Co., Inc.

[14] Dacron: Is a trademark of E.I. DuPont de Nemours & Co., Inc.

[15] Terylene: Is a trademark of Imperial Chemical Industries

To avoid hazards of skin irritation or sensitization, the following precautions should be taken.

1. Probably the most important consideration that will have the greatest effect in preventing injury is keeping yourself and your work area clean. Wash off any resin that comes in contact with your skin immediately with soap and water. Always wash up after using resins, even if you do not get any on you.

2. Protective clothes, safety glasses, and gloves will go a long way to keep skin contact to a minimum. Change clothes that get contaminated and have them washed before reuse.

3. Make sure you have proper ventilation. If in the field, stay up-wind from the resin so the fumes and dust will blow away from you. Respirators or dust masks should also be used.

3. Laminate Construction:

In field applications it will be found that sound laminate construction is vital to pipe strength and corrosion resistance. In glass-reinforced parts, the chemical-resistant laminate construction starts with an all important 10- to 20- mil resin-rich interior surface that creates a corrosion proof barrier, reinforced with chemical-grade glass mat or organic veiling.

The typical construction is:

a) Inner surface : 10- to 20- mil resin-rich inner liner reinforced with C grade surfacing mat or organic veiling.

b) Next interior layer: Generally about 100 mils thick consisting of at least two layers of 1 1/2 -oz mat reinforcement, 25 to 30 percent glass by weight.

c) Remaining thickness: varies with the laminate strength required; may be additional 1 1/2-oz mat reinforcement, cloth, or woven roving. In heavy construction requiring more than one layer of woven roving, 1 1/2-oz mat is used between layers of roving. Last layer of roving is always covered with 1 1/2-oz mat.

d) Exterior surface: Resin-rich surface reinforced with C grade surfacing mat plus an ultraviolet inhibitor.

4- Laminate Exposure:

It is important to determine at the outset of the design process the functional requirements of the end use. These considerations include:

Mechanical properties: Tensile, compressive, and flexural strength, elongation, impact resistance, hardness, density

Thermal properties : Thermal conductivity, heat distortion and heat resistance, thermal coefficient of expansion, flammability.

Electrical properties: Dielectric strength, arc resistance

Chemical properties : Resistance to acids, alkalis, and organic solvents, water absorption, resistance to ultraviolet radiation, and weathering.

Other requirements concerned with function may include surface finish, color appearance and machinability.

Obviously, it is important to describe in detail the service in which the FRP equipment will be used. Any details that are omitted could be key in the construction process of the equipment. For example, you should advise the fabricator of temperature fluctuations and cycling, as well as any upset conditions that the equipment might encounter. The fabricator should be informed of the potential need for a fire retardant material. You should also mention all known trace materials that might be present.

A common example is trace fluorides which would indicate to a fabricator that he sould use a synthetic rather than a "C" glass surfacing veil. Although many of these considerations may seem unimportant to you, they are very helpful to the fabricator. Because most engineers are concerned about a number of different environments, this description is usually included in drawing for a specific job rather than in a general specification.

5 A- Laminate properties:

In addition to the type of reinforcement and molding method used, shop practice, environmental conditions and duration of loading are other primary factors affecting the engineering properties of fiberglass reinforced laminates.

Careless production methods which lack proper handling and storage of basic materials and adequate quality control will produce laminates with defects that will reduce the engineering properties of the laminates. All fabricators should investigate their facilities and molding operations to improve their production methods and quality of their products.

When exposed to unfavorable environmental conditions fiberglass laminates can be adversely affected. To minimize these effects, fiberglass laminates should be properly selected and adequately protected with a suitable gel coat or resin coating.

Fiberglass laminates under long term continuous loading will exhibit a reduction in strength properties. This is a characteristic of the material that must be considered in design and proper stress levels must be selected to assure satisfactory long term service.

Shop practice

The physical and mechanical properties of a laminate can be considerably reduced by fabrication defects such as voids, wrinkles, delamination, washing, resin dryness or richness, crazing and foreign inclusions. Also shrinkage of the resin and temperature changes that occur during curing cause residual stresses in fiberglass laminates affecting their mechanical properties. These effects can be minimized with properly controlled curing cycles.

Environment

Fiberglass reinforced plastics can be adversely affected unfavorable environmental conditions. Extended periods of liquid immersion and exposure to extreme weathering conditions can cause some reduction in strength properties and these effects must be considered when selecting a laminate for a specific application.

Long term loading

As is the case with other structural materials, fiberglass reinforced laminates will fail under long term continuous loading at stresses below the ultimate stress for short term loading.

When selecting fiberglass laminates, designers must carefully consider the loading time intervals as well as the direction and magnitude of the applied loads. The judicious selection of working stress levels to allow for extended periods of loading is necessary to provide an adequate structure.

5 B- Sandwich construction

One of the biggest problems that the designer of an FRP parts is faced with is overcoming the low modulus of elasticity of fiberglass laminates. If the designer can increase the moment of inertia of a particular laminate without adding appreciably to the cost of weight, this major problem of FRP laminates can be overcome economically.

How can a designer achieve the necessary increase in moment of inertia? The most economical and simplest method is by use of sandwich construction.

A structural sandwich is formed by bonding two relatively thin and dense facings to a thick, low-density core. The core spaces the facings,transmits shear and provides most of the shear rigidity of the sandwich. The sandwich performs the same function as an I-beam in which the flange (facings) carry direct tension and compression loads, and the web (core) carries shear loads.

The core must perform the following functions:

1. Increase the flexural rigidity of the tank without significantly increasing its weight.
2. Provide sufficient shearing and compression resistance
3. Provide impact resistance
4. Provide thermal insulation and resistance to heat and cold
5. Prevent localized failure
6. Prevent damage due to vibration
7. Provide ease of fabrication.

Of primary importance, following the selection of basic components, is the bond between the skins and the core. The quality of this bond will affect the performance of the sandwich construction.

The demand for high strength, lightweight, thermally, insulating, and corrosion resistant structures in both the storage and transportation tank fields has grown significantly in the past decade. This growth is primarily due to high loading intensities coupled with high performance requirements, creating the need for more efficient materials and constructions.

6- Manufacturing processes:

Hand lay up:

A low to medium volume contact mold method suitable for making boats, tanks, housings and building panels for prototypes and for other large parts requiring high strength.

Process description:

A pigmented gel-coat is first applied to the mold by spray gun for a high quality surface. When the gel-coat has become tacky, fiberglass reinforcement (usually mat or cloth) is manually placed on the mold. The base resin is applied by pouring, brushing, or spraying. Squeegees or rollers are used to densify the laminate, thoroughly wetting the reinforcement with the resin, and removing entrapped air. Layers of fiberglass mat or woven roving and resin are added for thickness.

Catalysts and accelerators are added to the resin system to allow the resin to cure without external heat. The amounts of catalyst and accelerator are dictated by the working time necessary and overall thickness of the finished part.

The laminate may be cored or stiffened with honeycomb, balsa, foam plastic, or other materials to provide weight reduction or flotation.

Spray Up:

A low to medium volume, open mold method similar to hand lay-up in its suitability for making boats, tanks, tub/shower units, and other simple medium to large size shapes such as truck roofs, vent hoods, and commercial refrigeration display cases. Greater shape complexity is possible with spray-up than with hand lay-up.

Process description:

Fiberglass continuous strand roving is fed through a combination chopper and spray gun. This device simultaneously deposits chopped roving and catalyzed resin into the mold. The laminate thus deposited is densified with rollers or squeegees to remove air and thoroughly work the resin into the reinforcing strands. Additional layers of chopped roving and resin may be added as required for thickness. Cure is usually at room temperature or may be accelerated by moderate application of heat.

As with hand lay-up, a superior surface finish may be achieved by first spraying gel-coat into the mold prior to spray-up of the substrate. Woven roving is occasionally added to the laminate for specific strength orientation. Also, core materials are easily incorporated.

Compression molding:

A high volume, high pressure method suitable for molding complex, high strength fiberglas-reinforced Plastic parts. Fairly large parts can be molded with excellent surface finish. Thermosetting resins are normally used.

Process description

Matched molds are mounted in a hydraulic or modified mechanical molding press. A weighed charge of sheet or bulk molding compound, or a "preform" or fiberglass mat with resin added at the press, is placed in the open mold. (In the case of preform or mat molding the resin may be added either before or after the reinforcement is positioned in the mold, depending on part configuration). The two halves of the mold are closed and heat and pressure applied (225°-320°F, 150-2000 psi). Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. The mold is opened and the finished part is removed. Typical parts: Automobile front ends, appliance housings and structural components, furniture, electrical components, business machine housings and parts.

Cold press molding:

The process is an economical press molding method for manufacturing intermediate volumes of products (200 to 8,000), using low pressure, room temperature cure and inexpensive molds.

Process description:

Fiberglas reinforcement (preform or mat) is applied between matching molds, along with thermosetting resin. Woven roving may be added for strength. Molds may be gel coated. The molds are closed under moderate pressure (20 to 50 PSI) and the part is cured without heat other than the exothermic heat generated. Elevated molding pressures are not necessary.

Filament winding:

A process resulting in a high degree of fiber orientation and high glass loading to provide extremely high tensile strengths in the manufacture of hollow, generally cylindrical products such as chemical and fuel storage tanks and pipe, pressure vessels, and rocket motor cases.

Process description:

Continuous strand reinforcement is utilized to achieve maximum laminate strength. Reinforcement is fed through a resin bath and wound into a suitable mandrel (pre-impregnated roving may also be used).

Special winding machines lay down continuous strands in a predetermined pattern to provide maximum strength in the directions required. When sufficient layers have been applied, the wound mandrel is cured at room temperature or in an oven. The molding is then stripped from the mandrel. Equipment is available to perform filament winding on a continuous basis.

Continuous pultrusion:

A continuous process for the manufacture of products having a constant cross section, such as rod stock, structural shapes, beams, channels, pipe, tubing, fishing rods.

Process description:

Continuous strand fiberglass roving, mat or cloth is impregnated in a resin bath, then drawn through a steel die which sets the shape of the stock and controls the resin/glass ratio. A portion of the die is heated to initiate the cure. With rod stock, cure is effected in an oven. A pulling device establishes production speed.

7- Quality Control

Large reinforced plastic structures, such as covers, ventilating hoods, stacks and ducts are usually fabricated by hand lay-up techniques. Here the quality of the job and its performance is highly dependent on the workmanship as it affects the service life of the part involved.

Visual inspection provides a simple, easy means of judging the quality of the part. The appearance of reinforced plastic parts will differ from one manufacturer to the next. Appearance may not always be indicative or serviceability. The type of service for which a part is intended should be carefully considered during an evaluation of visual defects; for instance, a defect in a critical structure such as a tank or process vessel may not necessarily be considered as important in a less critical part such as a ventilating duct.

By placing a strong light behind the wall or section of an unpigmented structure, the inspector can judge the uniformity of the laminate, and detect air bubbles, dry spots, internal cracking and other conditions which may indicate potential weaknesses in the structure.

The condition of the surfaces may be an indication of the quality of the laminate construction. The inspector should be aware of the application for which the structure is intended; i.e., will both surfaces be in contact or exposed to similar or different corrosive environments? A smooth, true surface is generally a sign of a wellmade uniformly cured laminate. If exposed fibers exist on the corrosion surface, there is lack of continuity in the protective resin layer that is so vital to corrosion resistance. Exposed bundles of fiber indicate the likelihood of the absence of a surfacing mat or surfacing veil. Discoloration may be indicative or inadequate resin mixing or poor-cure practive (exotherms).

Well-prepared industrial specifications often call for cutting a section of the fabricated piece to provide coupons for testing.

These cuttings can be taken from overages on length or width or may be produced from the cutting of manholes. The resulting cross section will reveal the depth of the surface layer of resin as well as the shape and conformity of the laminate. Stressed areas often will be seen immediately in the form of internal cracks. The cross section of the test piece will give some indication of the bond between the layers of the reinforcement and the thoroughness of wet-out of the fibers. The location of the surface mat and the thickness of the protective resin-rich layer should be readily apparent.

Another on the site test that can be meaningful is the Barcol Hardness, but only when used to measure the relative hardness of pieces fabricated form the same system.

If the Barcol Hardness of a laminate falls short of the average ratings found in well-cured laminates of the same resin and reinforcement, then the inspector should immediately be suspect of an incomplete cure which will later show up in the form of poor corrosion resistance. The Barcol hardness, to be acceptable to the inspector, should always be greater than the reported hardness (by the resin supplier) of a fully cured clear (unreinforced) casting.

Summarizing, the quality control should be on the following items:

1. Thorough visual inspection
2. Uniformity of laminate and adherence to reinforcement specified
3. Glass content
4. Barcol hardness
5. Specified physical property tests
6. Overall workmanship

Generic types of resins

Resin type	Comments	End uses
General purpose polyester...	Generally not used for wet chemical service	Tote boxes, baptistries, boats, fishing poles, building materials, car and truck bodies.
Isophthalic polyester......	Good chemical resistance in many environments. Less expensive than those below.	Gasoline tanks, composite chemical tanks, refinery tank linings.
Bisphenol polyester Vinyl ester	Excellent overall chemical resistance. On of the major work horses of the industry.	Chemical piping, tanks, and structures
Hydrogenated bisphenol-A polyester	Excellent chemical resistance in many areas	Chemical piping tanks, and structures.
Chlorinated polyester	Excellent chemical resistance in many severe services, particularly chlorine	Chemical piping, tanks, and structures; with small quantities of Sb_2O_3 added provides highest fire retardancy for ductwork.
Epoxy	Provides good chemical resistance when heat-cured. More expensive than polyesters.	Chemical piping and tanks; superior alkaline resistance; good solvent resistance in some areas.